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THE ORDNANCE CORPS Shaped Charge RESEARCH REPORT

NUMBER 4-55

OCTOBER 1955

SPONSORED BY THE

ORDNANCE CORPS SHAPED CHARGE RESEARCH & DEVELOPMENT STEERING AND COORDINATING COMMITTEE

BALLISTIC RESEARCH LABORATORIES

ABERDEEN PROVING GROUND

MARYLAND

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THE ORDNANCE CORPS
SHAPED CHARGE RESEARCH REPORT

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THE ORDNANCE CORPS

SHAPED CHARGE RESEARCH REPORT

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THE ORDNANCE CORPS SHAPED CHARGE RESEARCH REPORT

TRANSACTIONS

OF THE

ORDNANCE CORPS SHAPED CHARGE

RESEARCH AND DEVELOPMENT

STEERING AND COORDINATING

COMMITTEE

MINUTES OF THE SHAPED CHARGE RESEARCH AND
DEVELOPMENT STEERING AND COORDINATING COMMITTEE MEETING
26, 27 July 1955

A. Opening of Meeting

The Seventh Meeting of the Ordnance Corps Shaped Charge Research and Development Steering and Coordinating Committee was held at Watertown Arsenal, Watertown, Massachusetts, on 26, 27 July 1955 at 1030 hours with Dr. L. Zernow presiding.

Col. A. P. Taber, Commanding Officer of Watertown Arsenal delivered the welcoming talk to the Committee. He discussed the complexity of the Shaped Charge Program, and commended the team work exemplified by the Shaped Charge Committee. Out of shaped charge research have come such diversified developments such as the barium-titanate fuze ("Lucky"), flash radiography for direct observation of rapid moving events and improvements in HEAT ammunition. Col. Taber concluded with wishes for the continued success of the Committee and his pleasure in being host to the Committee.

B. Recommended Practices Bulletin for Targets

Mr. A. Hurlich distributed for inspection only, copies of a "Recommended Practices Bulletin for Targets for Shaped Charge Research and Development". Arrangements were made for distribution of these bulletins through the Ballistic Research Laboratories to organizations represented at the Committee Meeting. It was requested that they be carefully examined by all who receive them. Comments, corrections and any supplementary information which it is considered desirable to include in this bulletin should be forwarded to Mr. A. Hurlich, Watertown Arsenal, Watertown, Massachusetts. It is planned to issue an addendum when it is warranted.

C. Plate vs Billet for Targets

The economics of steel billets vs steel plates as targets for obtaining shaped charge information was discussed. Mr. L. A. Foe of the Bjorksten Research Laboratories, Mr. J. Regan of the BRL, Dr. H. Winn of Firestone Tire and Rubber Company, and Dr. E. N. Clark* of Picatinny Arsenal presented their experiences and the costs involved. The detailed costs of material and labor is published in this issue of the Shaped Charge Report and will also be included in the "Recommended Practices Bulletin".

Dr. Pugh pointed out that where volume measurements are desired, the billet target is superior to the plate. However, the diameter of the billet must be large enough to avoid swelling and deformation of the target by the penetrating jet. Dr. Pugh also stated that performance-wise no differences have been detected between billet and plate targets. However, with better charges, small differences in the behavior of steel billet and steel plate might be detectable.

Col. Taber suggested that because of the high material costs involved in

*Picatinny paper will appear in the next issue of the Shaped Charge Research Report.

the use of steel targets, some thought be devoted to the use of other materials and forms which might be cheaper than steel, for example, targets consisting of containers filled with water or sand.

D. 57mm HEAT Development Program

Mr. C. E. Jacobson, Picatinny Arsenal, reported on the 57mm HEAT Development Program as follows:

1. Priority assignment to the project has been raised from priority 2 to 1-B by OCMA-590, through the efforts of Mr. Massey. However, the official OCM had not arrived at Picatinny at time of discussion.

2. Allotment of additional funds for this program had not been received.

3. Following the suggestion made at the previous Committee meeting for closer liaison between Picatinny Arsenal and Carnegie Institute of Technology, 25 cones were sent from Picatinny for inspection by Carnegie Institute. Results of inspections to date indicate little dimensional variations from the Picatinny results. Also noted was the fact that the results of inspections performed on the Camin manufactured electroformed liners were not as variable as had been previously believed.

4. The inspection procedure and the results obtained at Picatinny Arsenal were described as follows:

Two hundred liners were received by the Arsenal from Camin Laboratories. Six liners were checked for wall thickness at 3 circumferential and two longitudinal points. Maximum dispersion was 1.5 mils. Index angles met specifications. Five liners were chosen to check offset angle of flute (which requires cutting the liner) Offset angles varied from 27° to 42° where the drawing requirements were 30°. Maximum flute depth variation was .3 mil in any one liner. Generally, the liners which were reported to have done so poorly in compensating for spin do not show themselves to be inferior dimensionally.

One point noticed was that at the base of the flute, the poor performing liners had a sharp corner, where previously there was a radius. In the belief that this sharp corner may have induced a weakening of the liner and possibly break-up of the liner prior to its collapse, it was planned by Picatinny to investigate the performance of liners similar in all detail to the poor performing ones with the exception that the base would be filleted instead of sharp-cornered. However, to expedite the work on this program, additional funds would be essential. Dr. Eichelberger responded that photomicrographs of the liner profiles sent with the original drawings illustrated a radius at the base of the flute. Apparently, these profiles were not followed in the fabrication of present liners. However, there has been no past experience which would warrant an explanation for the poor performance being based upon the sharp vs the filleted corner. It was suggested by Dr. Zernow that instead of investigating what factors have gone into making these present liners perform so poorly, it would be of greater value to go back to the dimensions and configuration of the old Laify liner, which did show good spin compensation, and attempt to reproduce these in all details. Thus could the laboratory results be more rapidly applied to the development of the 57mm HEAT Service round. It was also suggested that Picatinny might obtain some 57mm fluted liners fabricated by Moe Light which give 7" penetration at 210 rps. The process involves a drawing-coining combination with the flute having a large radius on the exterior and a small radius on the interior.

E. Shaped Charges at Long Standoff Against Aircraft

Mr. R. Sewell of the Naval Ordnance Test Station, presented some of the current investigations on the effects of aluminum jets upon thin walled fuselages at long standoffs with charges ranging from 4" to 8-1/2" in diameter. This paper appears in this issue of the Shaped Charge Report. One conclusion which was drawn from the evidence presented was that in addition to damages from the jet perforating the fuselage wall, considerable damage to the fuselage resulted from forces generated within the fuselage after the jet perforated. Projected slides showed complete rupture of the fuselage as the result of an aluminum jet from an 8-1/2" diameter charge fired 60 feet from the fuselage and perforating the fuselage wall.

F. Ultrasonics in Non-Destructive Testing

Mr. C. Hastings of the Watertown Arsenal presented a movie on the use of the Sperry Ultrasonic Reflectoscope which had been modified for easy manipulation over irregular configurations as well as rough surface finishes. This has been accomplished by:

1. A series of weighted hinges which permits easy movement of the crystal over the surface of the object being inspected.

2. A series of curved or straight faced adapters, fitted over the crystal face which permits the crystal to ride over curved or flat areas.

3. A water coupling between the crystal and the inspected surface which permits the use of ultrasonic seeker over rough surface finishes.

Possible application of this type of reflectoscope for determining the penetration of a shaped charge jet into a steel target was discussed and Mr. Hastings expressed the opinion that the sensitivity of the reflectoscope could be made to differentiate between the bottom of the hole and any copper from the jet which may have been deposited in the hole. It was suggested that the application of the Ultrasonic Reflectoscope be considered.

G. R-Salt Explosives: Potential Use in Shaped Charges

Mr. C. E. Jacobson presented a paper on an explosive being investigated by Picatinny Arsenal which involves replacing some RDX with a material designated R-Salt. Mixture #38 currently used consists of 70% RDX, 27% R-Salt, 2-1/2% Phenanthrene and 1/2% 2-Nitrodiphenylamine. Mixture 38 is less sensitive to impact than Comp B and has a stability equal to 50/50 Pentolite. The solubility of RDX in R-Salt is approximately twice the weight of R-Salt. Results of tests with mixture 38 in shaped charges have not been very encouraging. However, the charges were found to be porous, chipped and the cones loose in the charge due to poor casting techniques. Further investigations are intended. The full paper appears in this issue of the Shaped Charge Report.

H. Surface Effects Investigation

The discussion on the Surface Effects Program which was on the Agenda for this meeting was deleted due to temporary delay in the testing program which is being conducted at Picatinny Arsenal. Some results may be available for the next meeting. A parallel investigation is currently under way at the Carnegie Institute of Technology, involving liners rejected by the Moe Light Company for slight defects. These will be fired to detect what effects these slight flaws have upon penetration.

I. Library of Congress Bibliography on Shaped Charges

Mr. J. Gibson of the Library of Congress announced that the Shaped Charge Bibliography prepared by the Library will be ready for distribution in August 1955.

J. Dr. Pugh expressed for himself and for the Committee the regrets felt at Dr. Zernow's departure from the Ordnance Corps and the Shaped Charge Committee.

K. Mr. M. Miller of OCO was nominated and unanimously elected as chairman of the Committee.

L. 90 - 106 - 120mm Caliber Evaluation Program

Dr. Zernow presented the current thinking on plans for firing the 90 - 106 - 120mm Caliber Evaluation Study. Plans are being formulated to add a tank evaluation phase where 9 rounds of each caliber as well as an additional 105mm modification will be fired against tanks and evaluated for lethal effectiveness. It is planned to fire these four sets of rounds against four identical tanks. Problems which arise in planning this phase are:

1. Selection of type and model of tank.

2. Which tanks components must be operative, which may be simulated.

3. Locations on tanks for point of impact of rounds.

Generally, it had been agreed at a previous meeting of the BRL (TBL & WSL), Firestone and D&PS that the fuel and ammunition compartments are too sensitive to be used to differentiate differences in effectiveness between the 90mm and 120mm HEAT round. Hence, the conclusion had been reached that all firings should be conducted into the crew compartment. Further meetings by the members directly concerned with this program is being planned. Mr. Salter, Detroit Arsenal, suggested that in conducting such a program, aluminum liners in the 120mm caliber should be included. With this larger caliber, the aluminum jet may achieve the penetration requirements not obtainable in the smaller calibers and the increased lethal effectiveness may more than compensate for the large caliber necessary to achieve the penetration.

Dr. Zernow agreed that such an experiment would be of value and agreed that it should be undertaken at a later date. However, the time available to complete the Caliber Evaluation Program would not permit these additional firings to be completed in this program. Inclosed as Appendix III is the Caliber Evaluation Testing Program on the 90 - 106 - 120mm HEAT Rounds as currently planned.

M. "DART" Lethality Evaluation

Dr. Zernow described the problems involved in assessing the lethal effectiveness of the "DART" Warhead as very similar to the problems faced in the 90 - 106 - 120mm Caliber Evaluation Program. Any conclusions arrived at on testing procedures for the Caliber Evaluation study may be applied to the "DART" study.

In conjunction with these two programs, Mr. Salter mentioned the availability of a wooden model of the JS III, constructed by Detroit Arsenal and containing all components based upon the most current information. He suggested that this model may be studied for possibilities of constructing simulated tanks or components instead of using American model tanks against which to test.

N. Editor of Shaped Charge Research Report

John Squier was proposed as the Editor of the Shaped Charge Research Report to replace Dr. Zernow. This was agreed upon.

O. Lethality Evaluation Committee

With the increased emphasis on lethality evaluation of shaped charge ammunition, the Shaped Charge Committee recommended that a Lethality Evaluation Committee be organized or if one is in existence, it be reactivated. Mr. Miller undertook to look into this matter.

P. Contributions to the Shaped Charge Research Report

Mr. Squier requested that all members of the Committee channel material of interest in the shaped charge field into the Shaped Charge Research Report. While there have been some contributions, many more can be used and are desired.

Q. Coordinated Metallurgical Program

Mr. H. Markus, Frankford Arsenal, described the purpose of the Coordinated Metallurgical Program. It was desired to conduct a study of processes which could be utilized in the fabrication of liners for HEAT ammunition. This program was subdivided as follows:

1. Picatinny Arsenal to study liner production methods involving

Meeting on Lethality Evaluation Against Tanks

A meeting was called at TBL on 21 July 1955 by Dr. Zernow for the purpose of discussing a test plan for the Tank Evaluation Study of the Lethality of Ammunition. In attendance were:

Pvt. Ring	D&PS
Mr. A. Pillersdorf	D&PS
Mr. J. Feroli	D&PS
Mr. D. Hardison	BRL
Mr. J. Hanna	D&PS
Capt. Fisher	D&PS
Dr. L. Zernow	BRL
Mr. I. Lieberman	BRL
Mr. J. Regan	BRL
Mr. G. Zeller	BRL
Mr. O. Miller	Firestone Tire & Rubber Co.
Mr. C. Dunkle	Picatinny Arsenal

The discussion revolved around plans for the current program on lethality evaluation for the 90-106-120mm Program and the "DART" Missile Program. In both cases, it has been agreed that a phase for evaluation against tanks would be highly desirable. However, the method for obtaining the desired information against tanks was not as clear.

After much discussion, the more obvious points which require decision in the evaluation against tanks were enumerated as follows:

1. The selection of the tank.

    a. Selection of model of tank.

    b. Number of tanks required

    c. Tank instruments which would be necessary and the possibility of simulating some of these.

    d. Operability of components which are desirable.

2. Selection of tank surface against which to fire.

    a. Location.

        (1) Turret.

        (2) Crew compartment.

    b. Obliquities of surface against which firings should be conducted.

    c. Proximity to suspension system.

3. Enumeration of type of data that would be recorded in great detail. The method to be employed in analysing the data should be clearly

defined so that proper assessment of damage could be performed in the initial stages.

The suggestion was made that the group attending this meeting consider themselves an Ad Hoc Committee, members to devote some thought to the problem of evaluation of lethality by use of tanks. Another meeting to be called to consider this question further.

COMMENTS ON TARGETS USED AT THE BALLISTIC RESEARCH LABORATORIES

J. M. Regan

Ballistic Research Laboratories
Aberdeen Proving Ground, Maryland

The target used by the Ballistic Research Laboratories is made up of 6" x 6" x 3" blocks stacked to a height great enough to absorb the entire jet. The shot is fired vertically and the penetration is determined by counting the number of plates completely penetrated and adding to this the penetration into the final plate. The penetration into this last plate is determined by cutting the plate vertically in a Racine hydraulic cut-off saw, Model 30-C thus exposing the cross section of the hole and permitting a measurement of the depth.

The target material most commonly used is 1020 steel. Purchased in quantities of fifty tons or more it is possible to obtain an entire heat from one furnace thus getting some assurance that the material is metallurgically consistent.

The plate is hot rolled to 3" thickness and shipped to the Proving Ground in sheets. At the Proving Ground the plates are flame cut into 6" x 6" x 3" blocks. Any slag present along the edges of the blocks from the cutting is removed but nothing further is done in preparation.

The cost breakdown for the preparation is given on a "per block" basis and the cost of each target with the penetration determined is listed later.

Fabrication Cost (per block)

Material	$1.44
Labor	.35
Supplies (acetylene, oxygen, etc.)	.19
Total fabrication cost per block	$1.98

Cost of Each Target (Average of 5 blocks per shot)

Five blocks @ $1.98 per block	$ 9.90
Cutting last block to determine penetration	.58
Total cost of target per shot	$10.48

The blocks are cut at the rate of 5 per hour or about 30 to 35 per day.

It has been suggested by Mr. Roe of the Bjorksten Research Laboratories that the use of round stock to make cylinders which would be fired into axially are more economical. A cylindrical target of 3" round stock 15" long equivalent to the stacked block target would cost $10.68 based on costs at Aberdeen Proving Ground. The expense of determining the penetration would increase the cost to well over $11.00.

No savings of either time or money is indicated by these figures. Adequate facilities for cutting, sawing and handling large quantities of steel plate are already available at Aberdeen Proving Ground and this fact contributes strongly to the low level of the cost. At other installations where such equipment is lacking it may be necessary to resort to other types of targets such as steel cylinders.

In the light of the above data no change is contemplated for the target structure presently used at the Ballistic Research Laboratories.

ABSTRACT OF PAPER

Presented By

L. A. ROE
BJORKSTEN RESEARCH LABORATORIES

At

THE SEVENTH MEETING OF THE ORDNANCE CORPS
SHAPED CHARGE RESEARCH AND DEVELOPMENT
STEERING AND COORDINATING COMMITTEE

Watertown Arsenal, July 26, 1955

USE OF STEEL BILLETS AS TARGETS IN THE EVALUATION OF THE PERFORMANCE OF SHAPED CHARGES

This paper describes the adoption of round steel billets, 10 to 20 inches long and 5 inches in diameter, as target material in place of one-inch thick mild steel plates. The work was performed under a contract from the Ordnance Corps, Picatinny Arsenal. All static firing tests were made with the 90 mm T108E40 HEAT shell.

Following the recommendations of the sponsor we first used 5 x 5 x 1-inch thick mild steel plates as target material. It was soon realized that the handling operations involved with the thousands of plates required in our test program would be very costly. Therefore we obtained some steel billets 20 inches long and 5 inches wide in diameter. The billets were Special Bar Quality C-1018 steel, showed Rockwell hardnesses of 67 to 70 and weighed about 114 pounds each. When the first static firing tests were made, it was found that about 200% more shots could be made during a given time. Also, time was saved in numbering plates, storing target material and in measuring the volume of the hole produced by the jet. The cost per pound of billets was less than that of plates when small lots of a few hundred pounds were considered. Later quotations on quantities of

40,000 pounds or over showed similar costs per pound of plates or billets. A July 21, 1955 quotation from Central Steel & Wire Company, Chicago, Ill. gave $5.60 per hundred pounds of 5" diameter H.R. C-1018 SBQ steel. Plates of the same quality steel were quoted at $5.50 per hundred pounds. These are mill prices. Costs of cutting were as follows:

Billets. $0.98 for first cut, each additional cut @ $0.60 each.

Plates: Saw cutting. First cut @ $0.75, each additional cut @ $0.24 each.

Flame cutting would be considerably less than saw cutting of plates.

The 20-inch long billets were difficult to handle and future tests will be made on 10-inch lengths which weigh about 57 pounds.

Depth of penetration is obtained by taking a rough measure by inserting a wire in the hole and cutting off the billet at that point. Then the bottom of the hole is drilled for exact depth if measurable quantities of copper are present. It was noted that much less copper was found in the billets than was found in the plates. This observation may be related to the fact that an orange-red column of flames was noted when billets were used in static firing tests. No flames were visible when plates were used.

The conclusion we have reached concerning plates versus billets is that billets are preferred when one type of round is being tested. If several types of rounds are under investigation, then the first 8 or 10 inches of the target should be a one piece billet while the balance may be one or two inch steel plates.

BJORKSTEN RESEARCH LABORATORIES

L.A. Roe

gc

L. A. Roe

Current Work on the Nitroso-analog (R-salt) of RDX for Application to Shaped Charges

C. E. Jacobson

Samuel Feltman Ammunition Laboratories
Picatinny Arsenal, Dover, N.J.

Picatinny Arsenal has been working for the past year on development of the nitroso-analog of RDX. The work has been directed toward producing a material of high purity and acceptable stability as well as utilization of this explosive in new castable compositions of improved performance.

R-salt, cyclotrimethylenetrinitrosamine, has 3 NO groups as compared to RDX, cyclotrimethylenetrinitramine, which has 3 NO_2 groups. R-salt is relatively cheap and simple to manufacture using ammonia, formaldehyde, sodium nitrite, water or ice, and a strong mineral acid. It has a melting point slightly over 100°C and a sensitivity to impact approximately the same as TNT. However, it has 20 to 30 percent more power than TNT in such tests as the spherical lead block and ballistic mortar. More important, probably, is the fact that R-salt will dissolve from 1½ to 2 times its own weight of RDX.

One R-salt composition, designated as Mixture No. 38, has been studied for its use in shaped charges. Mixture No. 38 has a heat stability slightly better than the 50/50 Pentolite used during World War II. Its sensitivity to impact value, obtained on the Bureau of Mines Apparatus (5-kg weight, 100 tests, 50 percent point), was 24 cm as compared to 17 cm for Composition B. Mixture No. 38 has the following composition; 70 percent RDX, 27 percent R-salt, 2.5 percent phenanthrene, and 0.5 percent 2-nitrodiphenylamine. The phenanthrene is present as a melting point depressant, the 2-nitrodiphenylamine as a stabilizer.

The quantity of R-salt available was small so the tests for evaluation of Mixture No. 38 were of necessity limited.

Rate of detonation sticks, made of convolute wound boxboard tubes, 18" long, 1" ID and 1/8" wall thickness, were loaded. Five sticks were loaded with Composition B and 3 with Mixture No. 38. Rates of detonation in meters per second, obtained on the rotating drum camera were as follows:

Composition B	Mixture No. 38
7600	8070
7660	8190

Composition B	Mixture No. 38
7740	8520*
7760	
7760	

*This figure was read from a poor trace and should be discarded.

One 90 mm M71 HE Shell was loaded with Composition B and another with Mixture No. 38. Both shell were buried in sand and initiated with a modified M54 Fuze. The Composition B-loaded shell produced 2340 fragments; the Mixture No. 38-loaded shell, 2716 fragments. The increase was fairly well distributed over the entire range of different sized particles.

Five shaped charges were loaded with Composition B and 5 with Mixture No. 38. The metal parts used were a copper cone from the T205 3.5-inch HEAT Rocket Head, machined to a .070" ± .001" wall thickness, silver soldered in a 10" long, 3.175" ID, .065" wall thickness, steel cylinder or tube. The charges were fired by means of 1.5" diameter tetryl pellets and U.S. Army Type II Special Blasting Caps into stacks of 5" x 5" x 1" mild steel plates (Brinell hardness - 116) at a standoff of 7½". The following penetrations, in inches, were obtained:

	Composition B	Mixture No. 38
	14.7	15.5*
	17.2	16.8
	19.9	17.3*
	20.5	18.5
	20.5	20.9
Average	18.55	17.[illegible]0
Std Dev	2.56	2.0[illegible]

*These 2 charges were loose in the cone-cylinder assemblies.

All of the shaped charges loaded with Mixture No. 38 were chipped around the periphery and, as noted above, two of the explosive charges were loose in the metal parts assemblies.

All of the above loadings were made by a single pour method. The Mixture No. 38 was poured at approximately 92°C and set at 85°C. Densities of 1.68 gm/cc and 1.67 gm/cc were obtained for Composition B and Mixture No. 38, respectively. Radiographs of the loaded items showed considerable cavitation indicating that the loading method needed modification. The items were tested in spite of the cavitation because so little of the H-salt was available.

It was concluded from the results obtained that R-salt compositions were definitely promising but that further development work was necessary. Two results of this work have already been produced. One is that the heat stability of R-salt has been improved by recrystallizing the material from boiling instead of merely hot isoamyl alcohol. The second result has been a new composition, designated as Mixture No. 59. This consists of 70 percent RDX, 27 percent R-salt, and 3 percent 2-nitrotriphenylamine. The 2-nitrotriphenylamine has been found to be a more effective stabilizer than 2-nitrodiphenylamine and also acts as a melting point depressant. Mixture No. 59 can be cast at 96°C and sets at 85°C. Its impact sensitivity value is 30 cm as compared to the previously mentioned 24 cm value for Mixture No. 38. It is planned to evaluate Mixture No. 59 in a manner similar to Mixture No. 38 as soon as sufficient R-salt becomes available.

Aluminized compositions containing R-salt also are being studied. One of the compositions containing 56 percent RDX, 27 percent R-salt, 14 percent (6-micron) aluminum, and 3 percent 2-nitrotriphenylamine has been calculated to be 166 percent as powerful as TNT. This composition pours easily and yields a satisfactory cavity-free cast.

When HMX has been substituted for RDX in Mixture No. 59, the composition is more difficult to pour but when cast yields charges of seemingly higher mechanical strength (difficult to break up by hand or even using a leather mallet).

Further work is planned on the R-salt/RDX compositions, R-salt/HMX compositions, and aluminized compositions, but the effort now is on R-salt/RDX compositions because funds are insufficient to perform all the work simultaneously.

THE EFFECT OF SHAPED CHARGES AT LONG STANDOFF AGAINST AIRCRAFT

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L. N. Cosner
J. Pearson

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Applied Research Division
Propellants & Explosives Department
U. S. Naval Ordnance Test Station
China Lake, California

ABSTRACT

The Naval Ordnance Test Station is continuing the investigation of the effects of shaped charges at long standoff against aircraft structures. The damage mechanisms are described, and an attempt is made to explain the processes active in producing vaporific explosions. The results of recent firings against aircraft structures prove conclusively that shaped charges can produce immediate or K-type kills against bomber style aircraft by means of vaporific explosions. (Pictures were eliminated from the report to facilitate publication.)

The U. S. Naval Ordnance Test Station has pioneered the study of the effects of shaped charges at long standoff against aircraft structures (Ref. 1). While none of the current aircraft missiles are using operational shaped charge warheads as yet, the work conducted at the Naval Ordnance Test Station has aroused the interest of missile designers both in this country and abroad, and promises to produce practical warheads which will have a good immediate, or K-type, kill probability at distances of 100-ft. or more.

In general, there are two primary damage mechanisms which act to produce a shaped charge kill. They are (1) perforation by a jet of high and hyper velocity particles and (2) vaporific explosions. The types of damage produced by the two mechanisms are quite distinct. The perforating jet produces holes in the structure while the vaporific or "Rinehart" effect produces damage mainly by internal blast. Which damage mechanism will be primarily operative in a given case will depend on such factors as the shaped charge size, cone geometry and material, standoff distance, and elevation.

Shaped charges which can produce perforation damage can also usually detonate bomb loads. Aside from bomb detonation, however, the perforation type damage mechanism becomes important as a K-kill producer only when the size and density of the fragment jet is sufficient to produce an entrance hole with a diameter which is significant when compared to the linear dimensions of the target. Perforation damage is the primary damage mechanism for shaped charges made with steel or copper liners, and is active, although not necessarily the primary damage mechanism, for shaped charges with zinc or aluminum liners.

The vaporific explosion exhibits many of the same characteristics as the detonation of a high explosive charge inside the aircraft structure. Separate aircraft subjected to the two types of damage both show the effects of internal blast. Structural failure mechanisms appear to be the same in both cases. In addition, both the vaporific explosion and the detonating explosive demonstrate a sharp cut-off in the damage produced as the size of the charge is varied. That is, as the charge size is increased the resulting damage remains fairly minor until a critical size is reached at which point the damage becomes catastrophic.

The shaped charge damage cut-off is shown by the effects of a series of scaled shaped charges with aluminum cones fired at 60° obliquity and 60 ft. standoff against aft fuselage sections of B-29 bombers. A 4½-inch diameter shaped charge produced only minor to negligible damage of the perforation type. A 6-inch diameter charge produced minor damage similar in appearance to that of the smaller charge but with a hole diameter about 2½ times as great. A 7½-inch diameter charge almost produced a K-kill with the appearance of vaporific damage. An 8½-inch diameter charge produced an obvious K-kill by means of extensive vaporific blast damage.

Several attempts have been made to explain the vaporific damage mechanism. Perhaps the most commonly accepted explanation has been that the blast effect produced by vaporifics was the result of the burning of the aluminum from the aircraft as well as the burning of the shaped charge liner material. Another explanation put forth by T. Triffett in an as yet unpublished work (Ref. 2) proposes a measure of the vaporific damage which would be proportional to the energy of the impacting particle, and inversely proportional to the volume of the enclosure, with modifications for the venting and the initial pressure in the enclosure.

Neither of these approaches fully satisfies the data obtained from the actual tests although Triffet's approach is quite good under certain conditions. While burning aluminum can release a large amount of energy, the conditions which prevail during the time that the damage is produced do not appear to permit sufficient oxidation of the aluminum to take place. Furthermore, the burning which occurs is carried on over such a relatively long period of time that it would not produce the explosive style damage that is observed. The damage produced by vaporifics occurs so rapidly that the venting of the volume makes little or no difference. For example, in the case of several fuselage shots with 8½-inch diameter charges the structural kill was well underway before the effects of venting could possibly be felt.

A more comprehensive approach seems to be one, which though it may have been considered at an earlier date, appears to have been passed over in favor of the combustion hypothesis. Namely, that the primary mechanism active in the vaporific effect is the rapid transformation of the kinetic energy of the jet into more random energy of the target fragments and the broken jet fragments after impact. At first glance this may appear similar to the hypothesis proposed by Triffett. There is a considerable difference, however, since the damage depends not on the energy of the impacting particle but on the amount of energy captured from the impacting particle and redistributed in the test enclosure.

The process is visualized as occurring in the following steps. First, the impacting particle strikes the target. Second, depending on the materials of the target and of the particle, the particle yields some of its energy to the target. This results in a mass of secondary particles being released from the back of the target. The impacting particle may also break into very small pieces which will continue into the target volume. Third, the above situation creates a region in space which contains a large number of particles that are traveling at a lower velocity than the particles in the jet which are following. Fourth, the next particles strike the particle infested region, break up, and yield their energy to this fragment cloud. And, lastly, the above process continues until an explosive expansion occurs.

As can be seen, the vaporific damage will be dependent on the liner material, the target material, and especially on the energy of the impacting jet. The most desirable jet material would be one which would shatter on impact, releasing a large portion of its kinetic energy to the random motion of the particles in the fragment cloud. From the delivery standpoint it would be very desirable to have the material stay together until it impacts the target. These are conflicting desires, but they are satisfied quite well by aluminum which has outperformed other liner materials in almost all tests involving vaporifics.

The order of performance of various liner materials which have been tested fits both the combustion and the energy capture hypothesis, for the materials tested which broke up readily on impact were also chemically active when dispersed as fine particles in air. Several of the commonly used liner metals in their order of descending ability to produce vaporific damage are aluminum, steel, and copper. Zinc can be rated as equal to or superior to aluminum under certain limited conditions.

The order of the same materials for their retention of ability to cause perforation-style damage as the standoff is increased is the reverse of the order for vaporific damage, copper being the best. Zinc definitely falls at the bottom of the list for this latter series. The zinc particles in the shaped charge jet are so fine that their velocity is greatly decreased in passing through the air, and at long standoff very little of the liner material reaches the target.

The long standoff effectiveness of a shaped charge appears to increase with altitude up to some limiting value at which point the damage levels off and remains fairly constant. Results obtained in the Naval Ordnance Test Station Controlled Atmospheres Laboratory using small shaped charges with aluminum cones and decreased chamber pressure to simulate high altitudes indicated that, in general, the degree of damage increased markedly up to altitudes of about 35,000 ft. and remained heavy up to 116,000 ft., the highest simulated altitude used (Ref. 3). The validity of extending the results of these experiments to full scale situations is somewhat questionable, but the trend of increasing effectiveness up to some "plateau altitude" would seem valid.

The question of which mechanism or what combination of mechanisms is responsible for the vaporific explosions produced by shaped charges at long standoff is an interesting and important problem. However, regardless of what explanation is finally accepted, the results of the recent experiments are still valid and of considerable importance to those involved in the design and evaluation of guided missile warheads.

Probably the most significant single finding of the recent shaped charge tests conducted at the Naval Ordnance Test Station is the fact that vaporific explosions can produce a K-kill to bomber style aircraft. This finding removes "vaporific damage" from the category of a bonus effect in damage evaluation to one of primary importance.

The other finding which should help to clear up some of the thinking concerning the use of shaped charges at long standoff against aircraft structures is that the extent of the vaporific damage appears to be directly related to the energy captured from the shaped charge jet by the target volume. This indicates that a small shaped charge of any type currently conceived cannot produce a K-kill by a vaporific explosion even at short standoff.

Tests now in progress at the Naval Ordnance Test Station and tests planned for the near future should make clear the relative importance of the various mechanisms which are active in producing vaporific explosions. As interest in the larger anti-aircraft guided missiles increases, the usefulness and applicability of shaped charges for producing K-kills at long standoff becomes of increasing importance and interest.

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SUMMARIES

OF

CURRENT WORK

Brief periodical summaries of progress, status of research programs, or transactions of committees, are welcomed from installations in this and directly related fields of endeavor.

PICATINNY ARSENAL SHAPED CHARGE COMMITTEE:

ABSTRACTS OF PROCEEDINGS, FIRST HALF OF 1955

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It was recently suggested, that from the Abstracts of recent Minutes of the Picatinny Arsenal Shaped Charge Committee, information of general interest and applicability be published here. This review covers the three meetings of the committee held 18 February, 15 April and 15 June 1955. It is believed that such a review not only avoids much repetition but also shows the progress of the various projects concerned better than can individual abstracts.

The following statements may summarize briefly the status of shaped charge research and development at the end of 1954:

1. Improvement in intercommunication among workers in the field and dissemination of new data to the engineer is shown by wider distribution of publications and reports, and by the implementing of a joint development program with Frankford Arsenal and BRL.

2. Elimination of defects in the liner, improvement of its basic design, and understanding of the significance of its metallurgical structure have so far advanced that further progress demands improvement of the explosive charge. Difficulties in fuzing have been so far overcome as to reveal the potential superiority in penetration by ballistic rounds due to their translational velocity.

3. The explosive charge has been improved through determining sources of nonuniformity, developing loading methods to eliminate them and applying new techniques to shape the detonation wave for greater efficiency. Progress has been made in applying the release wave theory to this study.

4. Development of defenses against the shaped charge jet, both passive and active, has been expedited. Study of shock wave interactions and experiment with liquids have thrown light on the unique resisting power of certain materials.

The information reported at the meetings of the committee during the first half of 1955 showed progress in all four of the foregoing phases, and is reported in sections numbered to correspond.

1. Dissemination of new data. The Arthur D. Little, Inc. shaped charge literature review was given considerable attention. The first progress report under the contract represented the first attempt to present their findings in a logical and orderly fashion. The members of the Ordnance Corps Shaped Charge Research and Development Steering and Coordinating Committee, however, found it inadequate, possibly because it covered earlier papers in which information was far less completely reported than in recent ones. The impression was general, at the January meeting of the committee, that ADL was doing the same kind of work as the Library of Congress and Michigan State College in the preparation of their bibliographies. The contractor had taken measures to coordinate effort with these agencies. The committee suggested further means of avoiding duplication and improving the ADL output. The contractor now appears to be approaching the original intention, to carry the work a step beyond the stage of abstracting-- to break the abstracts apart and rearrange the data in a logical pattern, much the same as the individual engineer would have to do for himself in utilizing the literature. Data from firing records at APG were recorded in a series of tables in which the descriptions of the various parameters, such as liner, charge and target, formed column headings. Some of the data previously recorded in abstract form have been rearranged in similar tables. Listed thus, it is easy to see the many gaps in the information generally provided by reports.

Almost never has the attempt to vary only one parameter at a time in shaped charge experiments succeeded. So often a variable not known to be important has been ignored. This detracts from the value of much of the older work. The gaps in our information may well serve as guides for future work.

2. Improvement of metal parts. Much attention is given to a type of liner fabrication process known as spinning, automatic spinning, shear forming, rotary extrusion, floturn, etc. It gives tolerances which are very close and, while no closer than possible with drawn liners, gives them automatically. While not as cheap as deep drawing for making liners by the million, it appears ideal for turning out modified items in small lots for development purposes and is very versatile. D of M and drawings for making the 90 mm T108E40 by this process have been purchased. A Lodge and Shipley automatic spinning machine has been ordered for this Arsenal. Proposals for a feasibility study of the process were evaluated here for OAC.

Also, knowledge of the effect of shear forming on rotation compensation, and development of procedures to measure this very important effect, are sought. Firestone is trying to correlate optimum rotation rate with the corresponding manufacturing parameters of the liner. The exact mechanism of the effect is proving difficult to "nail down". While large plastic deformation can be given a metal bar by merely twisting, it seems to be of a different kind from that imparted by automatic spinning. When Eastern Tool deep-drawn copper liners were given a spinning pass in a lathe, they provided no compensation at all, whether annealed or not. Here, of course, the effect was confined to the surface, but apparently, so is the property that gives "built-in" rotation compensation in shear-formed liners. The part of the operation at Craft which is responsible for their better quality liners may not be the spinning, but the final coining operation.

That metallurgical structure can affect the jet is shown definitely by experiments with liners made from single-crystal aluminum. Such liners appear to give bifurcation if the 1-1-0 direction is aligned along the cone axis, none if the 1-0-0 is so aligned, and partial bifurcation in intermediate alignments. Machining breaks up the single-crystal structure only at the surface.

Progress continued in rotation compensation with fluted liners and, equally important, in making electrodeposited dies, for impact extrusion of such liners, that stand up in production. Penetration of 8" with 57 mm cones has been obtained at rotation speeds of 150-200 rps. Results with 75 mm cones at Carnegie Tech indicate that compensation can be obtained in this calibre at 150 rps, even though the blanks were not up to standard. The fluted liner is definitely capable, if designed properly, of giving good penetration at its designed spin rate. Recent firings in the M38 with fluted liners also confirm the superiority noted in the M344 firings, of ballistic over static rounds in penetration. Eliminating the possible effects of all other factors leaves a difference of 2" still to be accounted for.

Fluted liners with index angles from 3° to 4.5°, although apparently good dimensionally, either gave poor penetrations or failed completely to compensate. (Increasing the index angle to about 5° would take the design to a region where optimum rate is less sensitive to small changes in this angle, but where there is less leeway for variation in flute depth.) Further elaboration of shock theory as applied to rotation compensation appears necessary to explain the effect of index angle.

Work with the double-angle liner continued. It has definite possibilities for wide application, and has been tried in the T230 and the 3.5" rocket heads with variable results. For instance, at Carnegie Tech some lots of spun double-angle liners were found to fall off in penetration with standoff much more than others. Combination of the double-angle liner with peripheral initiation can give some very good penetrations. The large dispersions still encountered merely seem to show that nobody has been smart enough to use the effect properly. Jet velocity measurements by flash radiograph at Carnegie Tech has shown no sharp change in the jet due to the break between the two angles. A triple-flash X-ray system designed for studies of this nature has been set up at this Arsenal.

Ductile cast iron liners in the 3½" rocket head gave 73% of the penetration obtained with copper liners. Fragments were formed in every firing, instead of a compact slug.

Modification of 75 mm M310A1 HEAT Shell by removing the shoulder from the inside of the case improved penetration slightly, but not as much as expected. At Firestone a [illegible] ring easier and less costly to make than the tapering one used in the standard 3.5" round gave slightly poorer penetrations, probably because of the complex effect of the change in end confinement.

At Frankford Arsenal, progress was made in the coordinated liner metallurgy program. Attempts to prepare 50 - 100-lb batches by shell molding encountered difficulties, but a batch of 120 - $3\frac{1}{2}$" liners was completed and prepared for final inspection. Mechanical properties are correlated with casting conditions in a forthcoming report. In powder metallurgy, shrinkage occurred during sintering, with appearance of cracks at the inside joint of wall and flange, but this problem has been solved. Electroforming gives highest density. A new planetary gear will permit electroplating several liners at once, with very good uniformity within the group. An extensive program has been initiated to coordinate bath conditions with physical properties of the electrodeposited metal. In die casting, the present effort stresses perfecting of dimensional control, and overcoming faults of the dies so as to provide liners which will be within the tolerances as cast.

3. Improvement of the explosive charge. The program for comparison of pressed and cast explosives was completed. Shell, 106 mm, M344 were press-loaded with A3 to density 1.65 and with RDX composition to densities in the range 1.66-1.70 for comparative penetration tests with cast compositions. Of the five pressed explosives tried, 3 gave results better and with less dispersion than cast Comp B.

A. D. Little, Inc. presses 80/20 RDX/TNT to density ca 1.75 with about the same sensitivity as Comp B. The constituents are coprecipitated from warm acetone solution poured into agitated cold water. Like hot pressing of RDX/TNT, however, such methods are difficult in large-scale production.

Deaeration of cast Comp B increased its detonation rate one per cent. On investigation of alternative methods of loading, particularly for improvement of lethality, Bjorksten Research Laboratories suggested the following: film technique for studying RDX-TNT distribution, colloiding by gelation agents to improve uniformity, wetting agents to improve charge-liner contact, mechanical removal of TNT crystallizing on inner surfaces, control of crystal orientation by use of electrets, and combination of pressure and vacuum casting.

R-salt, the nitroso-analog of RDX, appears far superior to TNT as an additive to RDX from the viewpoints of both power and sensitivity. An efficient stabilizer has been developed by Arthur D. Little, Inc. Shrinkage of the R-salt-RDX mixture on solidifying is much less than that of Comp B.

Difficulties in loading of shaped charges are being attacked by use of such expedients as a thin ring of solid paraffin, TNT or plastic around the base of the cone. In the M31 Rifle Grenade, however, such use of TNT gave poorer penetration and wider dispersion. Such a filler should give a reasonable shock impedance match with the explosive. In general the effect is to decrease penetration slightly but decrease variability. Such expedients should make no difference in rounds already loaded properly with HE, but may permit cast loading of more powerful explosives, too viscous to be loaded properly without great difficulty.

Tandem shaped charges offer the possibility of deeper penetrations than otherwise possible within limitations of caliber. For larger calibers, where extreme depth of penetration is not critical, such charges offer a possible means of insertion of incendiaries, etc behind the target. Promising results are obtained with use of a 3.5" T205 HEAT head as the rear charge and a 90 mm T108 head (with the flash-back tube) as the forward charge. The intention is that the jet from the rear charge traverse the flash-back tube of the forward charge, and that the slug initiate it. There is some evidence of successful double initiation, and good penetrations are obtained, but additivity is not conclusively established.

Aluminum body devices and copper shaping cones gave encouraging results in firing tests. Work at Carnegie Tech showed that thin aluminum inserts do not change the penetration; the jet formed is aluminum only at the tip, and penetration is the same as with a copper jet. The inserts, unlike the Breidenbach devices, perform in accord with the simple theory.

BRL has collaborated with PA on DART and LaCrosse. In the latter there is leeway for moving the liner back, reducing the weight of HE, and reusing the weight by addition of incendiary to the front end. In the DART, however, peak performance must be attained within forced weight restrictions. In the 3½" there is even less room for adjustment. Before deciding what extra weight can be tolerated, we must know better what loss of performance this means.

Carnegie Tech has developed a new theory of crater formation which predicts the relationship between fragment energy or velocity, and hole volume, for thin or thick targets. Arthur D. Little, Inc. suggest that Rayleigh-Taylor instability may be involved in some cases of liner collapse. They point out also that momentum interchange between slug and jet appears to have a simple formulation in collapse of fluted liners. However, the complementary effect of interaction of angular momentum between the explosion products and the entire liner must be at least equally important.

4. Defense, lethality, and beyond-armor damage. In further experiments with liquids at Carnegie Tech, various materials, mainly low density, have been tried in heavily confined cells. The density law is followed closely at densities above 2, but between this value and zero the equivalent thickness reaches a maximum, superimposing a "hump" on the simple parabola representing accord with the density law.

Special steel rod 5" - 7" in diameter and very uniform in hardness may provide better and cheaper targets than mild steel plates. Cutting costs, which are important, may be comparable.

At BRL, fragment distribution from homologously scaled charges as affected by rotation is being studied in the attempt to develop a more rational tank kill criterion than the 2" overmatch. It may be possible to specify lethality requirements more intelligently.

At the meeting of the Ordnance Corps Steering Committee 4 and 5 May, penetration theory was discussed extensively by representatives from the Rand Corp., Convair, BRL and others. A report of the proceedings has been submitted to this Journal.

L E T T E R S

T O T H E E D I T O R

This section of the Research Report is intended for the publication of brief discussions of current work of interest and for the announcement of important new developments which warrant being called to the attention of the other people in the field.

Manuscripts should be limited to 600 works or less. The Editors and the Editorial Board do not hold themselves responsible for the opinions expressed by the correspondents.

Predicted Effects of Confinement on Shaped Charge Performance* **

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The one-dimensional theory for confined explosive charges developed by Droesen[1] has been applied to shaped charges by means of the release wave theory, in the same fashion that the one-dimensional theory for unconfined charges was used earlier. The procedure is somewhat more complicated because of changes in procedure required for different ranges of c/m (ratio of explosive mass to liner mass). The details are described in a formal report[2].

The results of the calculations in general agree with the qualitative ideas developed intuitively in the past. Some of the results are shown in Figs. 1, 2, 3 and 4. Figures 1 and 2 show the collapse velocity and the jet velocity, respectively, as functions of the initial position of the parent liner element, for M9A1 copper cones of wall thickness of 0.0125 in. in standard charges. Calculations have been carried out for unconfined charges and for steel confinement of thicknesses of 1/16, 1/8, and 1/4 inch. The plots indicate that the confinement has no effect on the jet formed by the upper 2 1/2 cm. of the cone. For the lower part of the cone, the collapse velocity is generally increased by increased confinement thickness; with the effect being more pronounced as one approaches the bottom of the liner. Calculations have also been carried out for liners similar in all respects except wall thickness. Curves are shown in Figs. 3 and 4 for cones having wall thickness 0.050 inch. The notable feature is that the effect of confinement is evident nearer the top of the cone and that the effect is everywhere more pronounced.

Qualitatively, one would expect from these calculations that the depth of penetration and the penetration-standoff curve would be very little affected by the confinement of the charge. This agrees with available experimental data. On the other hand, one would expect considerable increase in the hole volume with the addition of confinement, especially for thick walled liners, and especially for the part of the hole formed by the rear of the jet. This is also in agreement with experiment. With regard to the more detailed behavior of the jet, one would expect that, although the total depth of penetration would be relatively unaffected by the addition of confinement, the relative contributions to the hole depth by various portions of the liner would be changed. Specifically, one would expect that, with increased confinement, the bottom part of the liner would contribute a greater fraction of the total depth of penetration. For this reason, it seems likely that details of liner mounting, quality of the charge around the base of the liner, etc. might be more important in heavily confined charges than in lightly confined or unconfined charges.

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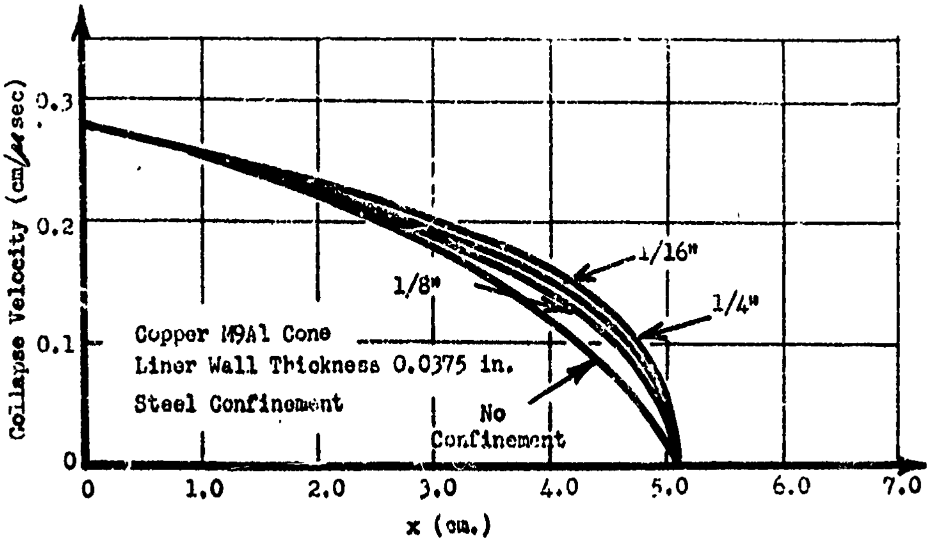

Figure 3 : Computed curves of collapse velocity as a function position of the liner element for cones 0.0375 in. wall thickness. Confinement varied as indicated.

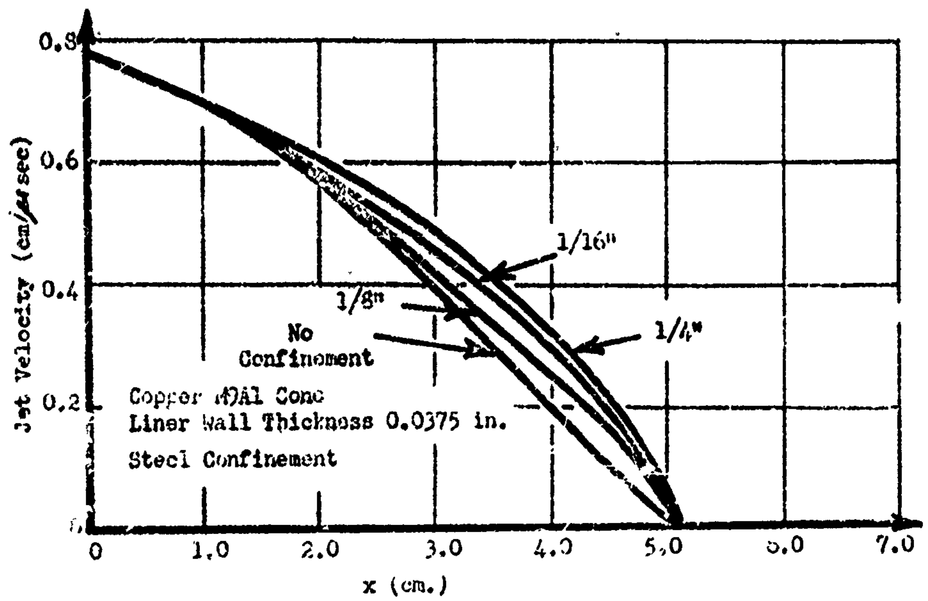

Figure 4 : Computed curves of jet velocity as a function of initial position of parent liner element, for cones 0.0375 in.

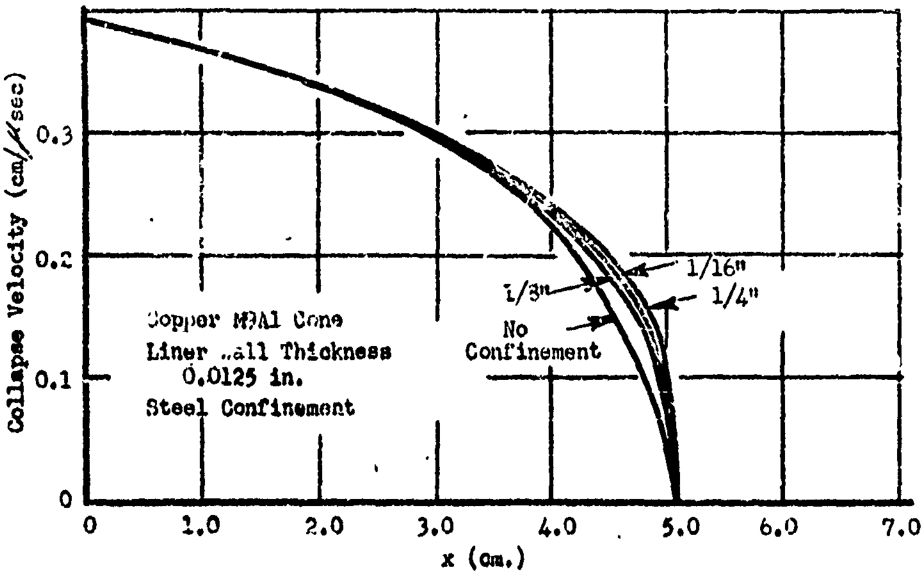

Figure 1: Computed curves of collapse velocity as a function position of the liner element for cones of 0.0125 in. wall thickness. Confinement varied as indicated.

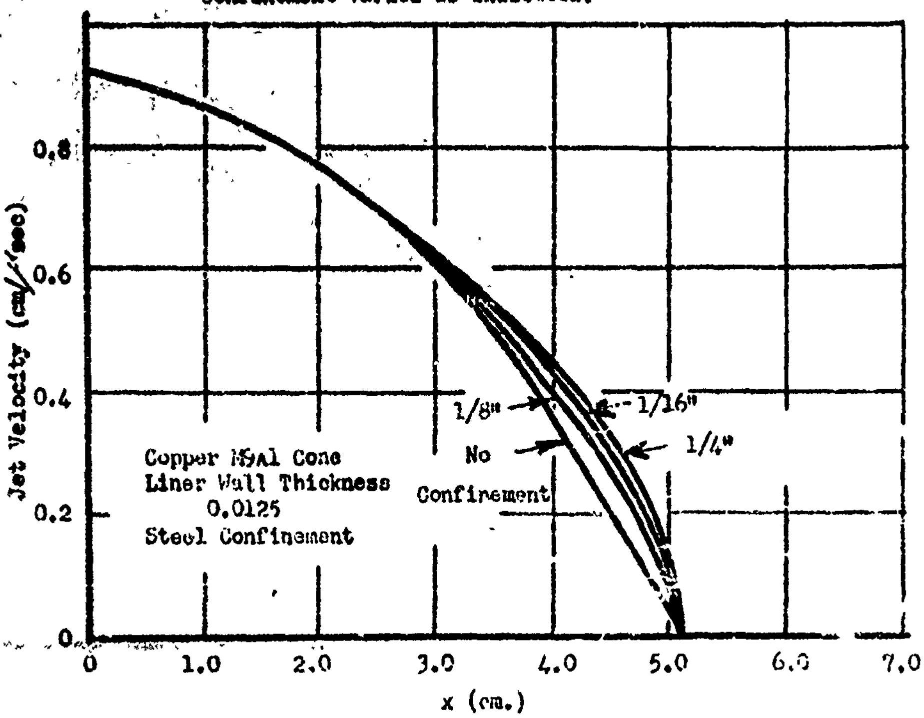

Figure 2: Computed curves of jet velocity as a function of initial position of parent liner element, for cones of 0.0125 in. wall thickness.

[*] The work described in this paper was carried out under Contract No. DA-36-061-ORD-453 with Ballistic Research Laboratories and was reported in the Third Quarterly Status Report, July 31, 1955.

[1] J. A. Dreesen, "Theory of One-Dimensional Charge with Confinement and Liner," Fundamentals of Shaped Charges, C.I.T. First Quarterly Status Report, Chapter No. IV, Contract No. DA-36-061-ORD-453, January 31, 1955.

[2] R. J. Eichelberger, "Predicted Effects of Charge Confinement on Jet Formation," Fundamentals of Shaped Charges, C.I.T. Third Quarterly Status Report, Chapter No. II, Contract No. DA-36-061-ORD-453, July 31, 1955.

The Distribution of Metals in a Jet from a Bi-Metal Liner* **

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In the course of their work with composite copper and aluminum liners, the Firestone Tire and Rubber Company has investigated the penetration of a 105mm charge containing a 100 mil copper liner and a 20 mil aluminum insert[1]. It was found that this combination gave penetrations which differed little from those obtained with the copper liners alone at a standoff of 7½ inches. If the composite liners produced aluminum jets, the penetration should be considerably less on the basis of the density law. It was felt, therefore, that, for the particular charge geometry and standoff involved, the division of mass between jet and slug, as a function of distance along the cone axis, was such that the jet contained a large proportion of copper along most of its length.

This might be demonstrated by determining experimentally the jet velocity V and penetration rate U associated with a particular jet element at a given point in the target. These quantities are related to an effective jet density $\lambda \rho_j$ by the equation[2]

$$\lambda \rho_j (V - U)^2 = \rho_t U^2$$

in which the strengths of target and liner have been neglected. For a jet composed of one metal, $\lambda \rho_j$ should decrease with increasing penetration depth because of the breakup factor λ. For a mixed jet, ρ_j also depends on the depth. In particular, if the jet is primarily aluminum near the tip, but contains a large proportion of copper farther back, then it is quite possible that $\lambda \rho_j$ will increase considerably in the region where the copper begins to predominate.

A limited number of these charges was made available to C.I.T. for such an investigation. Streak camera records of the progress of the jet through spaced target plates served as the basis for estimating V and U as functions of position in the target.

Figure 1 is a diagram of charge, target and resulting record. The heavy lines are those actually observed - the slopes representing velocities of different parts of the jet. The average penetration rate through a given plate is represented by the slope of the dotted line connecting the incident and emergent jet velocity lines. (The instantaneous penetration rate, of course, varies continuously through the plate.) We associate with this average U a V which is the average of the incident and emergent jet velocities. We can then calculate $\lambda \rho_j$ for a given plate position z. The target used consisted of 2 in. thick mild steel plates 4 in. apart, at a 7½ in. standoff. The results for two copper and two composite cones are listed in Table I.

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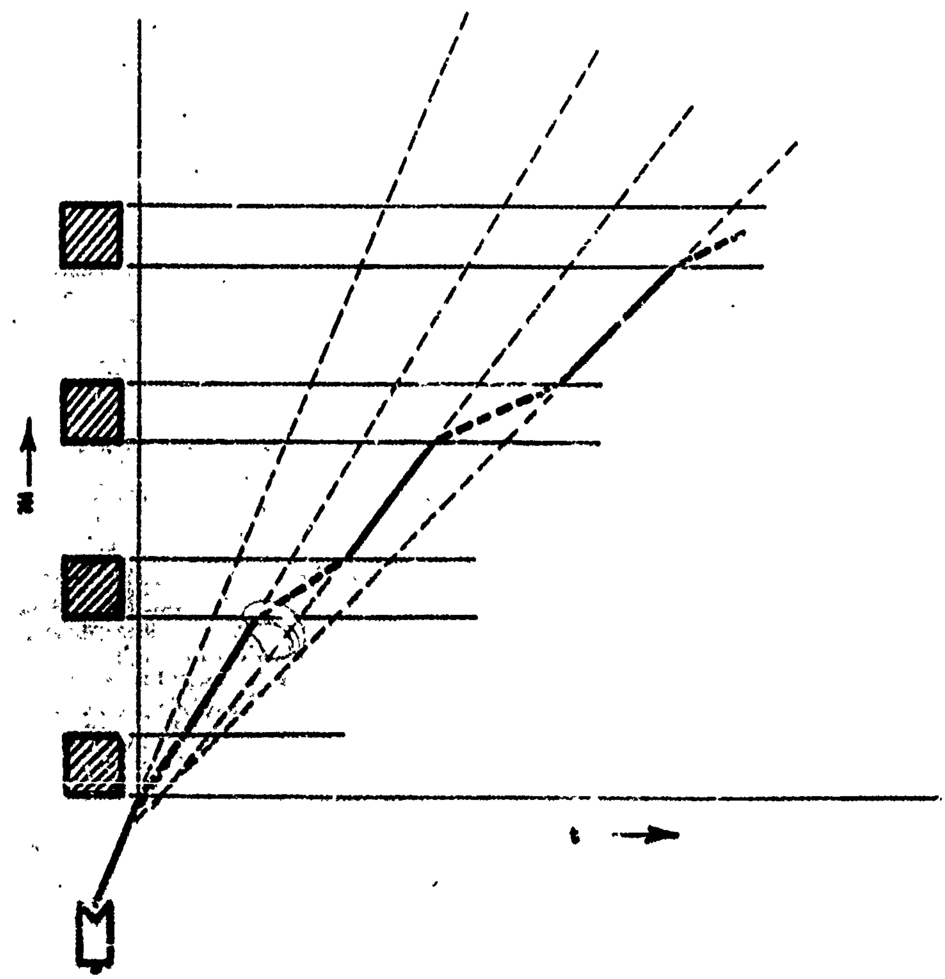

Figure 1. Streak record of jet passing through spaced target plates.

Table I.

z (in.)	Copper λ/ρ_j	Copper λ/ρ_j	Composite λ/ρ_j	Composite λ/ρ_j
0	7.2	6.1	1.9	1.9
6	6.2	6.3	4.9	1.1
12	4.7	6.1	5.5	4.0
18	5.5	3.7	3.3	2.0
24	3.9	1.7	1.1	

The results indicate that the first one or two plates are penetrated by a predominantly aluminum jet, after which a considerable proportion of copper is apparent. This means that, in a solid target at the same standoff, roughly 3 or 4 in. of the total 20 or so inches of penetration can be attributed to aluminum; the remainder is due to a jet in which copper predominates (on a weight basis).

This picture was substantiated qualitatively by an examination of the target plates. The hole in the first plate was coated with metal which was quite definitely the color of aluminum. In the rest of the plates the coating was yellow and had the appearance of brass.

It was found by Firestone that, at higher standoffs, the composite cone is definitely inferior to the copper cone. The jet has lengthened sufficiently so that the aluminum front end plays a more important role. At a given standoff, increasing the wall thickness of the aluminum insert should decrease the penetration since the copper will not begin to predominate so soon. Inserts of 0.04 in. aluminum, tested by Firestone, gave considerably smaller penetrations.

*The work described in this paper was carried out under Contract No. DA-36-061-ORD-453 with Ballistic Research Laboratories and will be reported in the Third Quarterly Status Report, July 31, 1955.

[1] "Battalion Anti-Tank Project," Firestone Tire and Rubber Company Fortieth Progress Report, November 1953, Contract Nos. DA-33-019-ORD-33 and DA-33-019-ORD-1202.

[2] R. J. Eichelberger, "Re-Examination of the Theories of Jet Formation and Target Penetration by Lined Cavity Charges," CEL Report No. 1, Carnegie Institute of Technology, Contract No. DA-36-061-ORD-394, June 1954.

Note on the Distribution of Metals in a Jet from a Bi-Metal Liner* **

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The distribution of metals in a jet from an aluminum lined copper cone manufactured by the Firestone Tire and Rubber Company has been investigated on the basis of the jet velocity distribution, the penetration rate into steel, and the hydrodynamic equation of penetration. The results, which were reported in a previous communication to this journal[1], indicated that the jet behaves like an aluminum jet during a relatively small part of the penetration process, and assumes the character of a copper jet for the major portion of the penetration.

This picture can be compared, at least qualitatively, with the theory of the collapse process by predicting the relative amounts of copper and aluminum entering the jet from any point on the cone. The prediction can be tested by direct examination of the slugs.

The division of mass between jet and slug as a function of distance along the cone axis is estimated from the charge geometry alone, by means of release wave calculations[2] and collapse theory[3]. It is then possible to estimate the amount of copper entering the jet along with the aluminum. Specifically, if M_c and M_a are the mass per unit area of copper and aluminum respectively in the undisturbed cone, then the total mass per unit area of the cone is $M_c + M_a$, and the portion entering the jet is

$$\frac{dm_j}{dm} (M_c + M_a) \quad ,$$

where dm_j/dm is the predicted fraction of cone mass which goes into the jet. Thus the mass of copper per unit area which enters the jet is

$$m_c = \frac{dm_j}{dm} (M_c + M_a) - M_a \quad .$$

Dividing by the density of copper we obtain the thickness of copper contributing to the jet.

The calculated division of the wall, over the major portion of the cone, is shown in Figure 1 for aluminum thicknesses of 0, 0.020, and 0.040 inches. The percent copper by weight can be estimated from these results. For the 20 mil insert the value ranges from about 54 percent at the tip to about 75 percent near the tail. For the 40 mil case the range is approximately 13 to 55 percent. It is reasonable then to expect the 40 mil case to approach the performance of a true aluminum jet as predicted by the density law - that is, the penetration should be around $\sqrt{2.7/8.9}$ (≈ 0.55) times that of the copper jet. The ratios found experimentally by Firestone for stand-offs of 7.5, 15, and 30 in. were 0.57, 0.48, and 0.51 respectively[4].

Slugs from liners having inserts of 0, 20, and 40 mils were recovered in rock wool and sectioned at approximately 0.2 in. intervals. No aluminum is apparent in the first two cases. In the 40 mil case an irregular cavity, partially filled with aluminum, is found along the axis of the slug. The cavity is quite large near the apex and begins to taper off toward the base. This result indicates that the estimates of dm_j/dm are too high, inasmuch as they predict that all of the aluminum will enter the jet, even in the 40 mil case.

*Received 9 August 1955

**The work described in this paper was carried out under Contract No. DA-36-061-ORD-453 with Ballistic Research Laboratories and was reported in the Third Quarterly Status Report, July 31, 1955.

[1] G. M. Bryan, "The Distribution of Metals in a Jet from a Bi-Metal Liner." (EDITORIAL NOTE: See page 362, this issue)

[2] R. J. Eichelberger, "Predictions of Shaped Charge Performance from the Release Wave Theory," Status Report No. 1, Chapter I, Fundamentals of Shaped Charges, Contract No. DA-36-061-ORD-394, Carnegie Institute of Technology, January 31, 1954.

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[4] "Battalion Anti-Tank Project," Firestone Tire and Rubber Company, Fortieth Progress Report, November 1953, Contract Nos. DA-33-019-ORD-33 and DA-33-019-ORD-1202.

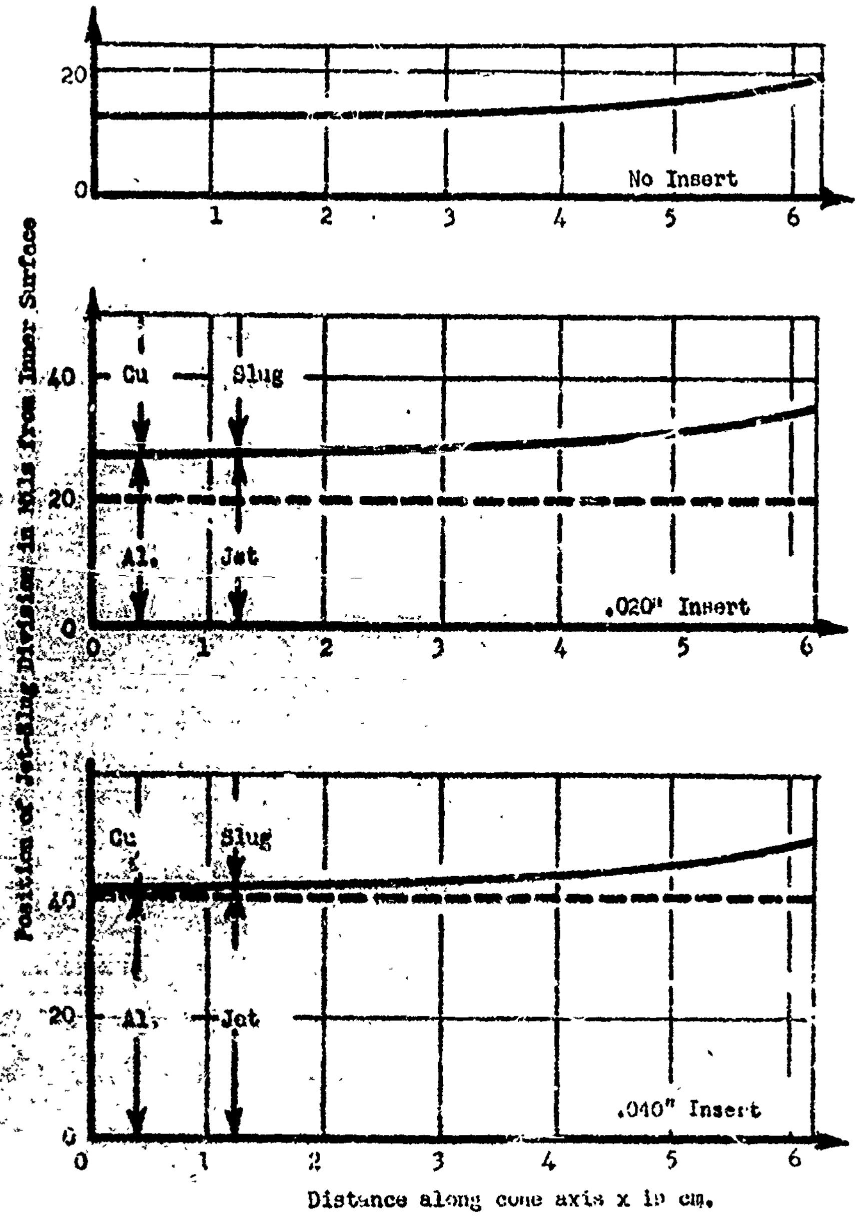

Figure 1. Theoretical division of cone wall material between jet and slug.

Elongation and Fracture of the Jet* **

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A first attempt has been made to develop a quantitative formulation for the elongation of the jet formed by a charge of known dimensions and materials. In this formulation, the simplest possible assumptions have been made, in lieu of information concerning the ductile behavior of materials under the conditions experienced by a jet after its formation. The chief purpose has been simply to find a basis for quantitative analysis of experimental observations concerning jet elongation and break-up, that can be modified as more information is obtained.

The basis of the formulation is the definition of jet elongation by means of the equation

$$e = \frac{(dz/dV)_{t,x}}{(dx/dV)_{t^*,x}} - 1 \quad , \qquad (1)$$

where e is elongation; z is the instantaneous position at time t of the jet element formed from the liner element initially at position x and having the velocity V ; t^* is the value of t at the instant a jet element is formed. Combining this definition with the generalized theory of jet formation[1,2], the elongation can be written as

$$e = \frac{(t - t^*) \frac{dV}{dx}}{1 - V \frac{dt^*}{dx} + \frac{d}{dx} \left[r \tan(\alpha + \delta) \right]} \qquad (2)$$

where r is the radius of the liner element initially at position x , α is the cone half-angle, and δ is the Taylor collapse angle. Proceeding further, and assuming that the jet remains ductile until the elongation increases to a value e_c , when fracture occurs, we find for the position in space, measured from the top of the cone, at which fracture occurs

$$z_c = z(V, t^*) + V\, e_c\, (dx/dV)_{x,t^*} \qquad (3)$$

By way of illustration of the implication of this formulation, calculations have been carried out for 1 5/8 in. (M9A1) copper cones in standard C.I.T. charges. The jet characteristics were calculated by means of the

**Received 9 August 1955

release wave theory[3] and the generalized theory of jet formation. The position at which fracture of the jet occurred was then calculated for each jet element, assuming that each element fractures when e_c for that element rises to 5.25, and plotted as a function of the velocity of that element. The predicted curves of dV/dz (the velocity gradient in the jet) at the time t* is shown for 22 deg. and 44 deg. cones of wall thickness 0.0375 " in Fig. 1 and the corresponding curves of z_c as a function of jet velocity in Fig. 2. Figures 3 and 4 show a similar set of curves calculated for 44 deg. cones having wall thicknesses 0.0125 in. and 0.0375 inch.

*The work described in this paper was carried out under Contract No. DA-36-061-ORD-453 with Ballistic Research Laboratories and was reported in the Third Quarterly Status Report, July 31, 1955.

[1]E. M. Pugh, R. J. Eichelberger and N. Rostoker, "Theory of Jet Formation by Charges with Lined Conical Cavities," Journal of Applied Physics, Vol. 23, No. 5, pp. 532-536, May 1952.

[2]R. J. Eichelberger, "Re-Examination of the Theories of Jet Formation and Target Penetration by Lined Cavity Charges," CEL Report No. 1, Contract No. DA-36-061-ORD-394, June 1954.

[3]R. J. Eichelberger, "Predictions of Shaped Charge Performance from the Release Wave Theory," Transactions of Symposium on Shaped Charges - Dec. 7-9, 1953, B.R.L. Report No. 909, p. 192.

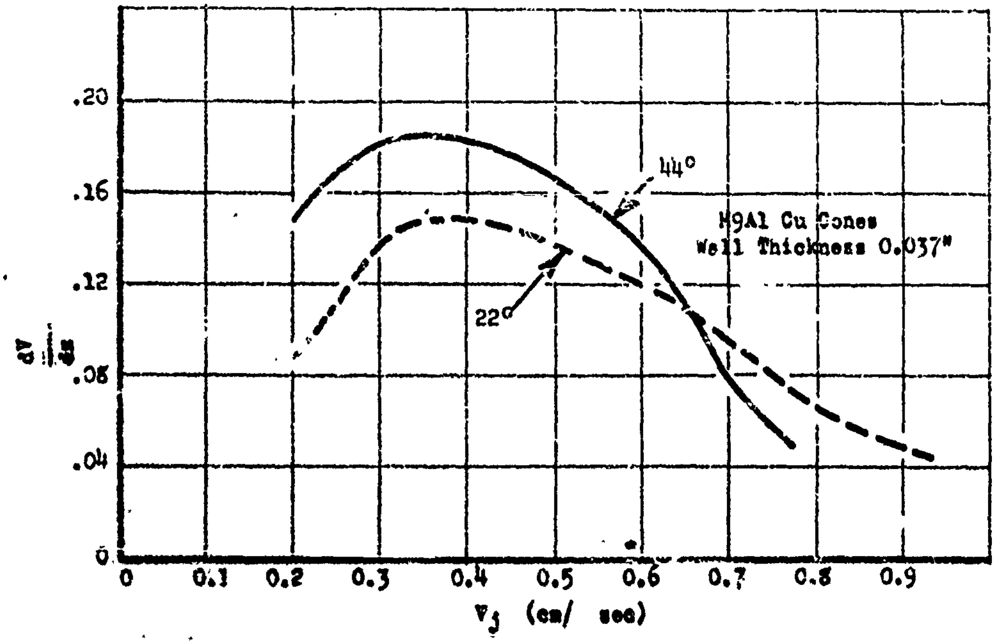

Fig. 1 Computed velocity gradient (taken at the instant of formation, t°, for each jet element) as a function of jet velocity.

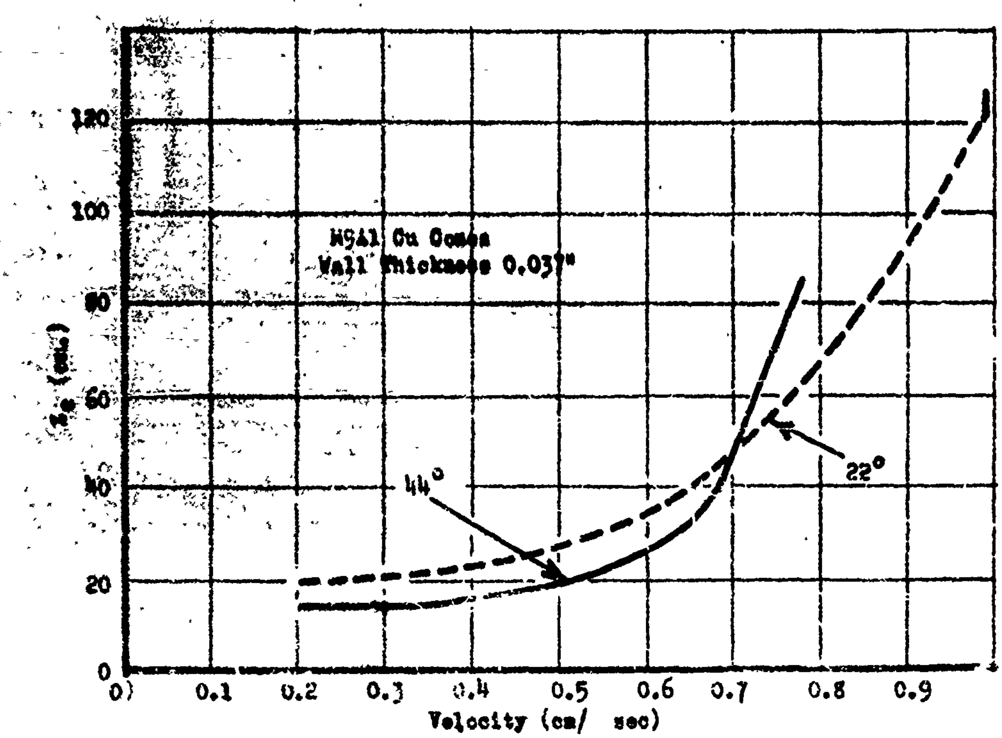

Fig. 2 Computed values of location at which fracture occurs in the jet as a function of jet velocity; elongation assumed to be constant, equal to 5.25.

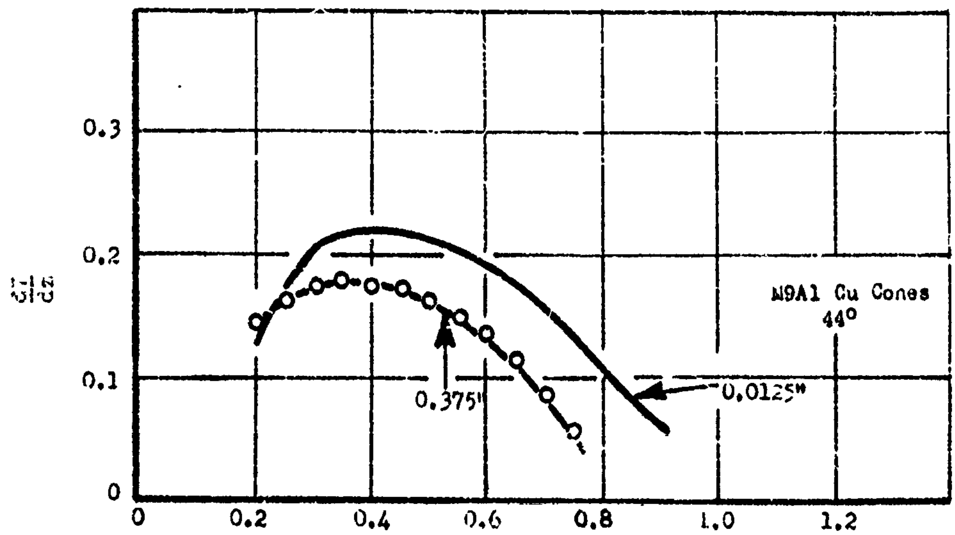

Figure 3: Computed velocity gradient (taken at the instant of formation, t*, for each jet element) as a function of jet velocity.

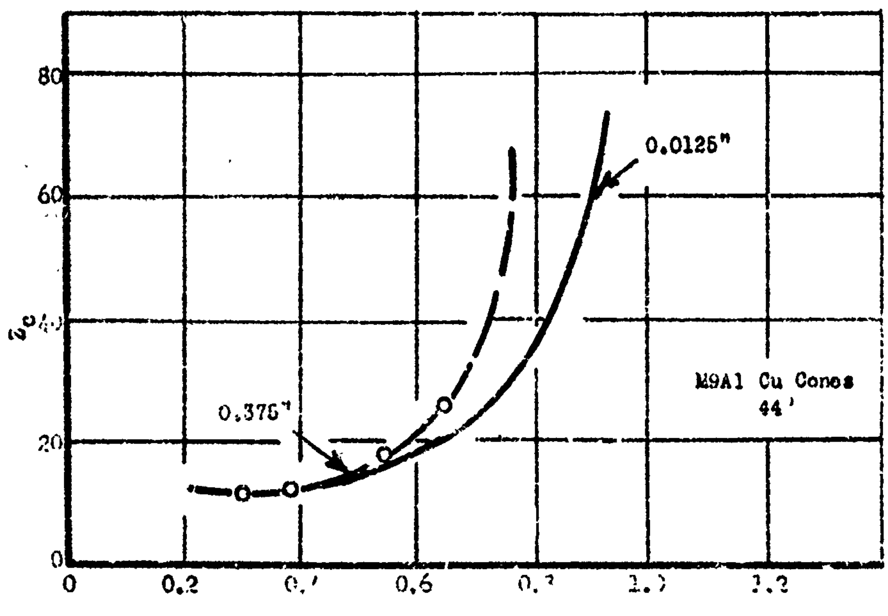

Figure 4 Computed values of location at which fracture occurs in the jet as a function of jet velocity; elongation assumed to be constant, equal to 5.25.

Compensation by Fluted Liners* **

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We have recently[1] described a theory that was developed for the prediction of compensation frequencies for fluted liners of the (s,s) type. Specific assumptions that were made regarding the relative values of various liner parameters limited the usefulness of the theory, so that no comparisons were possible with known experimental results. We have since extended the theory to include more general liner designs, and calculations may now be made for many designs for which experimental results are available.

We have carried out the calculations, which prove to be rather lengthy, for two specific designs. The parameters were chosen to represent an element 0.70 in. from the liner base for the series $\{0.044(16 \times 0.010)(s,s)(\eta)\}$, for which experimental results[2] are available. Unfortunately, however, through a misunderstanding the wall thickness chosen for the calculations was probably about 10 per cent too large. We compare the results of these calculations with experiment in Table I, the experimental results being taken directly from Fig. II-1 of reference 2.

η = Index Angle (deg.)	ω_c = Calculated Compensation Frequency (r.p.s.)	ω_o = Observed Optimum Frequency (r.p.s.)
6.3	− 65.0	− 85
20.7	+160.7	+170

In view of the numerous assumptions involved in the theory, the agreement between the calculations and experiment is phenomenally good. It should be remembered, however, that the observed optimum frequency is necessarily a sort of weighted mean value of the compensation frequencies for all liner elements. We would guess, however, but without much basis, that this should increase the degree of agreement. We are not prepared to guess the effect of the differences in wall thickness on the observed agreement, nor are we prepared to guess the effect of variations in other parameters chosen in the calculations, which in one case, at least, is probably unrealistic.

These calculations, as well as further calculations which are planned and which will throw more light on the potentialities of the theory, will be discussed more fully later.

**Received 9 August 1955

*The work described in this paper was carried out under Contract No. DA-36-061-ORD-453 with Ballistic Research Laboratories.

[1] J. A. Dreesen, "Theoretical Treatment of Fluted Liners," Third Quarterly Status Report, Chapter V, Carnegie Institute of Technology, Contract No. DA-36-061-ORD-453, July 31, 1955.

[2] K. R. Becker, E. L. Litchfield and R. J. Eichelberger, "Experimental Observations with 57MM Fluted Liners," Second Quarterly Status Report, Chapter II, Carnegie Institute of Technology, Contract No. DA-36-061-ORD-453, April 30, 1955.

57 mm. Fluted Liners* **

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Experimental results from a series of 57 mm. fluted copper liners show that one lot of the series has performance characteristics making it suitable for use in the 57 mm. HEAT round.

The series of liners presented here have the general C.I.T. designation 048 (16 x .0175) (SS) (Ø) with a base diameter of approximately 1.89 inches. The ten lots making up the series differ nominally in index angle; the indexing ranging from 0.5 deg. to 21 deg.

All liners discussed in this paper were cast into a 1.883" diam. x 3.78" Composition B charge, confined in a plastic charge head, rotated in a shaft rotator, and fired at 2 cone diameters standoff into stacks of 4" x 4" x 1" mild steel plates.

The performance data from the ten lots are summarized in Figure 1, which is a plot of optimum frequency as a function of index angle; corresponding penetrations are found in Figure 2, a plot of penetration vs. optimum frequency. Taking into consideration both performance characteristics (optimum frequency and penetration), it appears that Lot W-11, which is represented by the first point on each plot has the most interesting performance characteristics; it has an optimum frequency of almost 200 r.p.s. and penetration of 7.3 inches at this frequency. Better penetrations are obtained for lots in the indexing region of from 1 1/2 deg. to 12 deg.; however, it may be noted by inspecting Figure 1 that optimum frequencies are too low to make these lots particularly interesting. For the lots with index angles greater than 12 degrees, Figure 2 shows the penetrations to be quite low.

The promising performance results from Lot W-11 prompted further investigation of these liners. 100 additional liners were pressed and and twenty of these were cast up and fired; the spin rate was 210 r.p.s. which is at or near the frequency at which field rounds are rotated. Penetration results from these shots are tabulated below:

Shot #	Pen.	Shot #	Pen.	Shot #	Pen.	Shot #	Pen.
1	6.2	6	7.2	11	7.2	16	7.[illegible]
2	8.0	7	6.4	12	6.7	17	7.0
3	8.1	8	6.2	13	7.4	18	8.0
4	5.2	9	6.3	14	3.6	19	7.2
5	7.2	10	5.0	15	7.7	20	6.9

**Received 9 August 1955

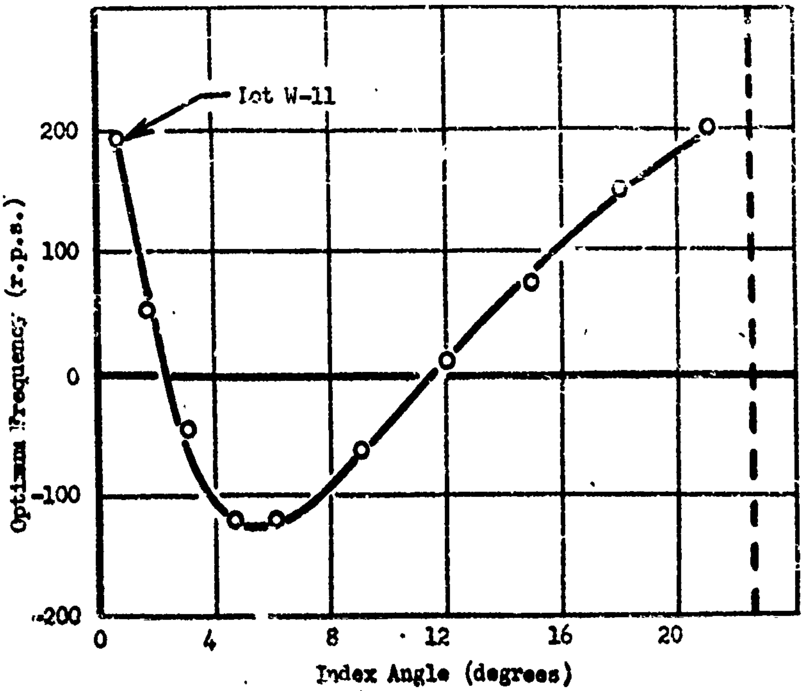

Fig. 1 Plot of optimum frequency vs. index angle.

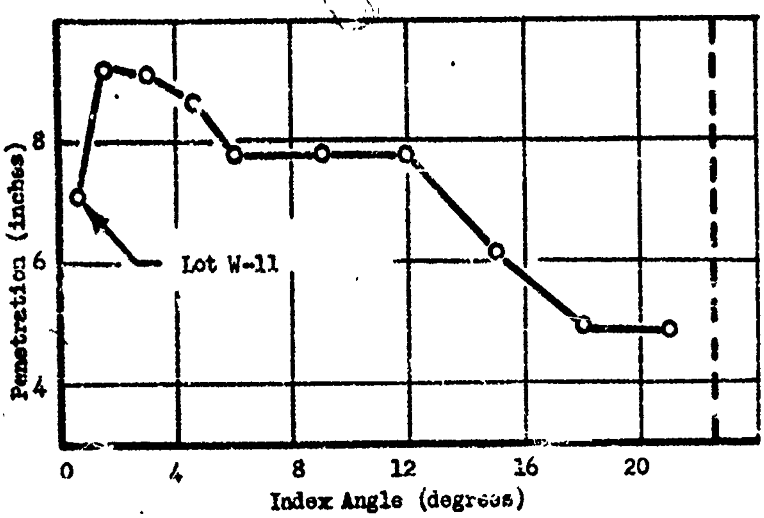

Fig. 2 Plot of penetration vs. index angle.

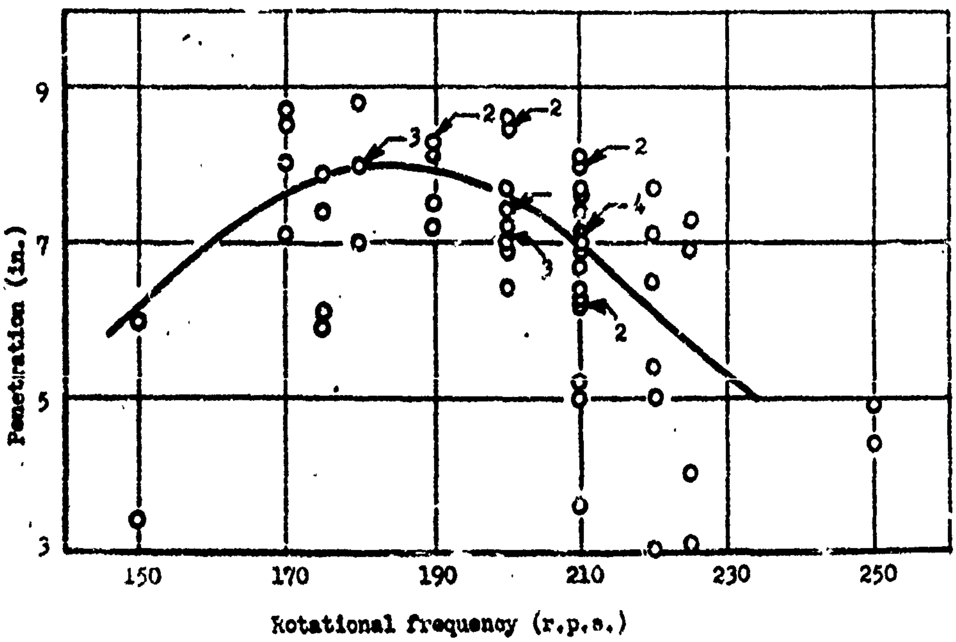

Figure 3: Plot of penetration vs. rotational frequency for a lot of 57 mm liners with the designation 048 (16 x .0075)(SS) (1/2°).

The average penetration is 6.8 inches with a standard deviation of 1.1 inch. Deleting the 3 poor shots (#4, #10, #14) an average penetration of 7.1 inches is obtained.

In order to determine more precisely the optimum frequency of these liners, twenty five additional liners were cast up and 5 each fired at 170, 180, 190, 200 and 220 r.p.s. The results from these twenty-five shots; the twenty shots fired at 210 r.p.s., and 19 shots from the original group of W-11 liners are the basis for the plot of penetration vs. rotational frequency presented in Figure 3. An optimum frequency of 185 r.p.s. and penetration of 8.0 inches is interpreted with the assistance of a symmetrical curve. The curve does not represent penetrations at 175 r.p.s. and 200 r.p.s. very well. All the shots at 175 r.p.s. are from the original group of cones received and all shots lying above the curve at 200 r.p.s. are from the new shipment, as were shots in the 170 r.p.s. region; consequently it appears that 1/2 to 1 inch penetrations are obtained with cones from the new shipment. An investigation of the difference between the two shipments is pending.

*The work described in this paper was carried out under Contract No. DA-36-061-ORD-453 with Ballistic Research Laboratories.

75MM Fluted Liners* **

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Preliminary tests with 75mm fluted liners suggest the feasibility of a liner design with performance characteristics suitable for use in the 75mm HEAT round.

The serration depths are a nominal scale of a successful 57mm liner design. The 75mm liners tested have the conventional C.I.T. designation [.069(16 x .024)(s,s)(5½ deg.)]. The number .024 in this instance is the flute depth (inches perpendicular to cone axis) at a reference plane located 0.394 in. from the cone base. The flute depth versus cone height relationship is linear.

The liners were cast into a 2 3/8 in. x 4 3/4 in. Comp. B charge, confined in a plastic (Synthane) charge head, spun on a wire rotator, and fired at 4 3/4 in. standoff into stacks of 4 in. x 4 in. x 1 in. mild steel plates. The performance curve is given in Fig. 1. An optimum frequency of 132 r.p.s. is interpreted with the assistance of a symmetrical curve. The interpreted penetration at this frequency is 10 in. which corresponds to about 95 per cent of the penetration obtained with the smooth parent cone fired statically. Also of interest is the best shot at 150 r.p.s. which gave 10.4 in. penetration. Variability of penetration at optimum frequency and 150 r.p.s. is rather large, however, no greater than with the smooth blanks fired statically and can very possibly be attributed to a combination of poor quality smooth blanks and the base alignment technique used in charge casting.

Results from this group of liners are somewhat encouraging since, with slight changes in liner design, an optimum frequency of 180 r.p.s. and comparable penetration should be entirely feasible. Nine other groups of 75mm fluted liners with indexing varying from 0 deg. to 21 deg. have been received. Further tests and a more complete investigation of 75mm liners is under way.

*Received 24 May 1955

**The work described in this paper was carried out under Contract No. DA-36-061-ORD-453 with Ballistic Research Laboratories and will be reported in the Third Quarterly Status Report, July 31, 1955.

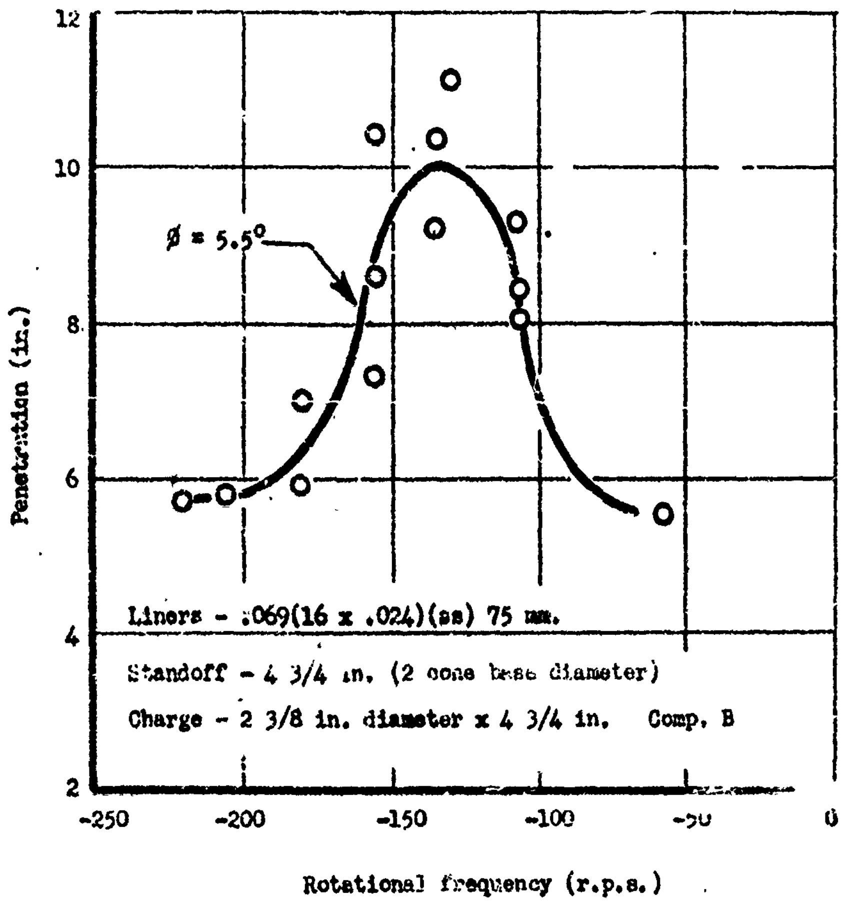

Figure 1. Plot of the performance data for a lot of 75mm fluted liners.

FLASH RADIOGRAPHIC STUDY OF SPIN COMPENSATION WITH 105MM FLUTED LINERS (II)*

J. Simon

Ballistic Research Laboratories
Aberdeen Proving Ground, Maryland

Flash radiographic studies of fluted liners at the BRL have been reported previously.(1)(2) The Firestone Tire and Rubber Company has provided us with another 105mm cone design(3) DRD-393, Item 2 (60 flutes) to be fired statically and at various rotational frequencies, the jet to be observed flash radiographically. The design parameters and performance(3) are as follows: 60 external pressed flutes, wall thickness .1048", flute depth .0129", radius to flute crest 1.617", spin compensation frequency 62 rps,** and optimum penetration of 20.0 inches in mild steel.

Examination of the radiographs shows that the fluted liner fired at its optimum frequency produces a jet similar to that from a statically fired smooth cone, while the statically fired fluted liner produces a jet like that from a smooth liner under rotation.(4)

Radiographs of the jets from the DRD-393, Item 2 design are shown in Figures 1, 2, 3, 4, 5 and 6. The transition from the badly broken jet in Figure 1, which was non-rotated, through the slightly broken jet in Figure 4, which was rotated at 60 rps, to the broken jet in Figure 6 at 75 rps is correlated with the observed penetration performance under rotation.(3) The radiographs of the jets (Figures 3 and 4) at spin frequencies 45 rps, 60 rps, respectively are very similar, and the penetration performance was 19.6" at 45 rps when fired into a mild steel target at a standoff of 7.5".(3)

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(1) Zernow, L., and Simon, J., "Flash Radiographic Study of Spin Compensation with 105mm Fluted Liners", Shaped Charge Journal, 1, No. 1, 96, July 1954.

(2) Zernow, L., and Simon, J., Flash Radiographic Study of Special Liners, BRL Report No. 936, APG, Md., July 1955.

(3) Supplement to Progress Report No. 29, on the 105mm BAT Project, Contract No. DA-33-019-ORD-33, Firestone Tire and Rubber Company, Defense Research Division, Akron, Ohio, December 1952.

(4) Zernow, L., Effects of Rotation, Critical Review of Shaped Charge Information, BRL Report 905, Chapt VII, APG, Md., May 1954.

* Received 4 August 1955.

** The convention for algebraic sign of the direction of rotation has been taken as positive if rotation of the projectile is clockwise when viewed from the rear. This is the normal situation for artillery with a right hand twist of rifling.

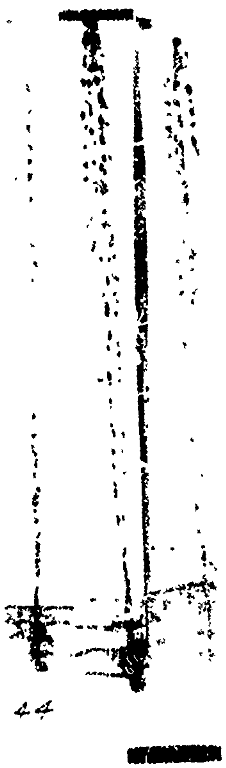

Figure 1

Flash radiographs of the jet from a 105mm fluted liner, design DRD-393, Item 2, non-rotated. The jet is broken and polyfurcated.

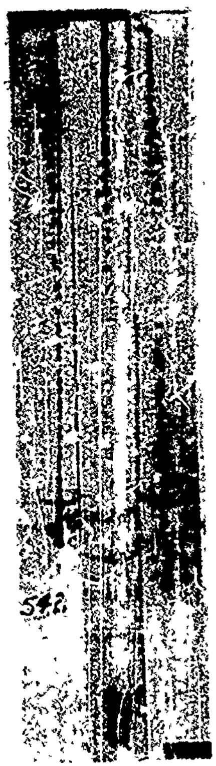

Figure 2

Flash radiographs of the jet from a 105mm fluted liner, design DRD-393, Item 2, rotated at a spin frequency of +30 rps. The jet is polyfurcated to a lesser degree than the jet in Figure 1.

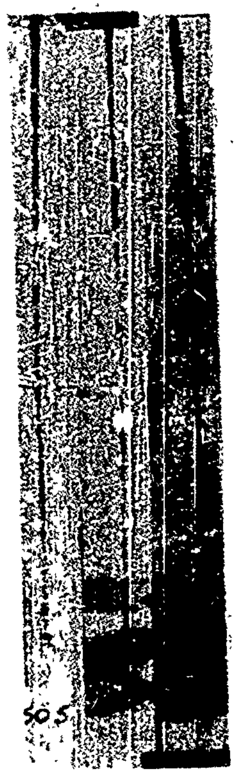

Figure 3

Flash radiographs of the jet from a 105mm fluted liner, design DRD-393. Item 2, rotated at a spin frequency of +45 rps. The jet is approaching continuity.

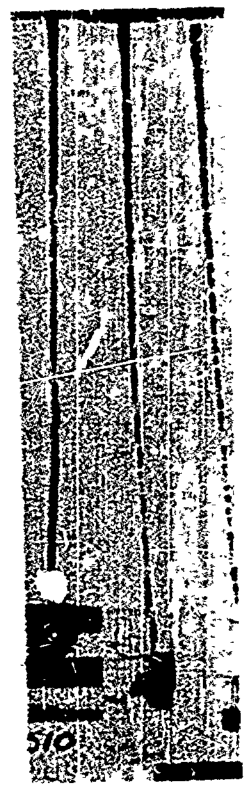

Figure 4

Flash radiographs of the jet from a 105mm fluted liner, design DRD-393, Item 2, rotated at a spin frequency of +50 rps. The jet indicates the proximity of the spin compensation frequency has been reached.

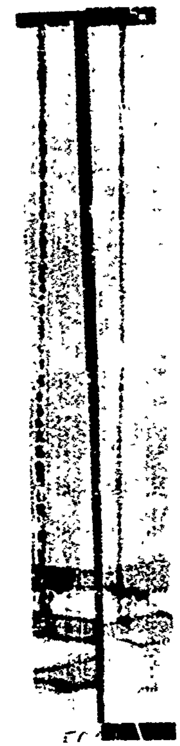

Figure 5

Flash radiographs of the jet from a 105mm fluted liner, design DRD-393, Item 2, rotated at a spin frequency of +60 rps. The jet has begun to bifurcate.

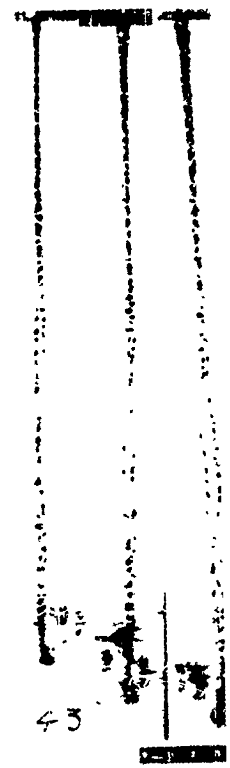

Figure 6.

Flash radiographs of the jet from a 105mm fluted liner, design DRD-393, Item 2, rotated at a spin frequency of +75 rps. The jet is broken and polyfurcated.

FLASH RADIOGRAPHIC STUDY OF SPIN COMPENSATION IN 105MM COPPER LINERS MANUFACTURED BY CONTROLLED "SPINNING"*

J. Simon
L. Zernow**

Ballistic Research Laboratories
Aberdeen Proving Ground, Maryland

The Ballistic Research Laboratories have obtained from the Craft Manufacturing Company (Chicago, Illinois) two lots of 105mm spun liners made by a controlled manufacturing process. The liners were copper cones made to drawing ORD-75-2-510D2, with a 42° apex angle and a 0.105" wall thickness. These liners were machined with a flange to fit the heavily confined 105mm penetration assemblies used at this laboratory.

The manufacturing parameters of rotation of mandrel, rate of feed of forming wheel, and direction of mandrel rotation were chosen so that these liners would be spin-compensated at +30 rps.(1) The "angle of distortion",(1) a correlation between spin compensation frequency and the manufacturing parameters suggested by the Firestone Tire and Rubber Company, was used as a criterion in the spinning process. During the manufacture of Lot 1 liners, the "angle of distortion" was found to be 15° instead of the predicted 22° for a spin compensation frequency of +30 rps. Investigation at the Craft Manufacturing Company revealed that a 3/4 hard copper blank stock had been obtained from the commercial supplier. Consequently a lower "angle of distortion" equivalent to a 2/3 A rate of mandrel rotation was obtained from the manufacturing process.(2) To obtain the proper spin compensation frequency, Lot 2 liners were manufactured from material with the proper metallurgical specifications.

Flash radiography(3)(4) was utilized to study evidence of spin compensation characteristics imparted to jets of both lots of liners by this method of manufacture. The jets obtained from these liners, while rotating at

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(1) Thirteenth Progress Report of the Firestone Tire and Rubber Company on Design and Development of Cartridge HEAT, T-300 for 90mm Gun, T119, under Contract No. DAI-33-019-501-ORD(P)16, Firestone Tire and Rubber Company, Defense Research Division, Akron, Ohio, May 1954.

(2) Verbal communication by Dr. H. Winn of Firestone Tire and Rubber Company, 14 April 1955.

(3) Zernow, L. and Simon, J., "Flash Radiographic Study of Spin Compensation in Shear Formed Liners (ITE)", Shaped Charge Journal, 1, No. 1, 100, July 1954.

(4) Simon, J., Flash Radiographic Study of Anomalous Jets from 90mm Liners Manufactured by Rotary Extrusion, BRLM 907, BRL, APG, Md., July 1955

**Dr. Zernow is now with Aerojet-General Corporation, Azusa, California.

*Received 2 August 1955

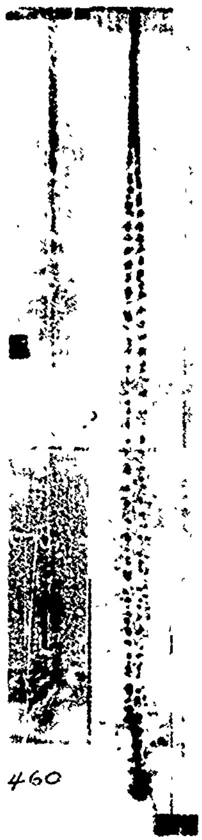

Figure 1

Multiple flash radio graphs of the jet from a 105mm spun copper liner (Lot 1). The spin rate was -30 rps. Note the jet is badly fragmented and polyfurcated

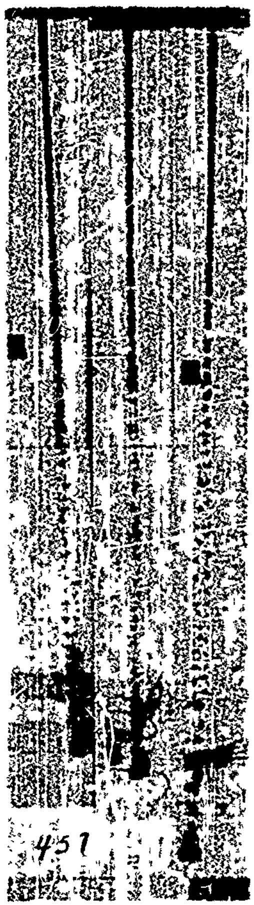

Figure 2

Multiple flash radio-graphs of the jet from a 105mm spun copper liner (Lot 1). The round was fired non-rotated

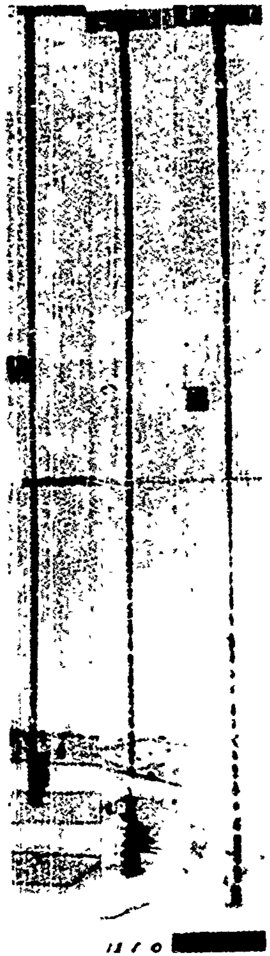

Figure 3

Multiple flash radio-graphs of the jet from a 105mm spun copper liner (Lot 1). The spin rate was +20 rps. The jet is approaching spin compensation frequency.

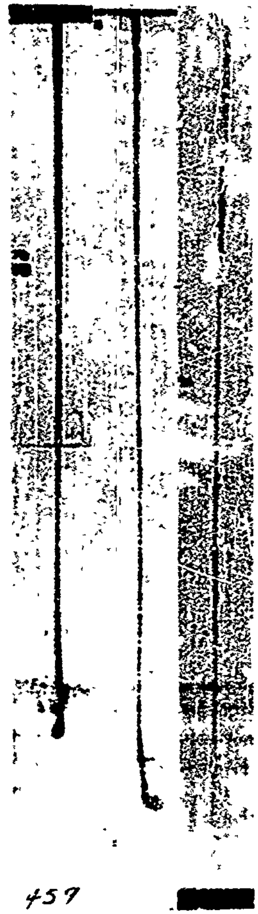

Figure 4

Multiple flash radio-graphs of the jet from a 105mm spun copper liner (Lot 1). The spin rate was +30 rps. The jet is practically continuous and spin-compensation is evident.

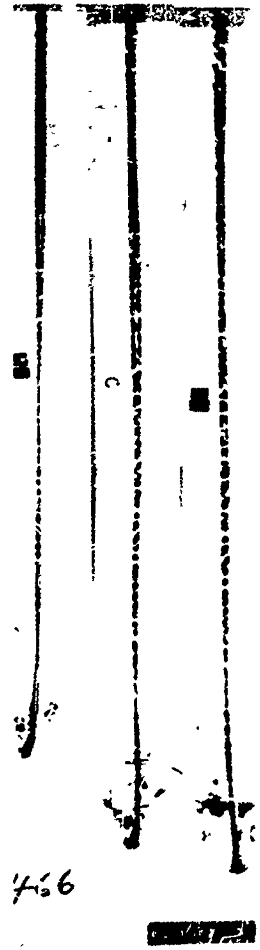

Figure 5

Multiple flash radio-graphs of the jet from a 105mm spun copper liner (Lot 1). The spin rate was +45 rps. The compensation frequency has been passed, and the jet is bifurcating.

Figure 6

Multiple flash radiographs of the jet from a 105mm spun copper liner (Lot 2). The spin rate was -30 rps. The jet is badly fragmented and polyfurcated.

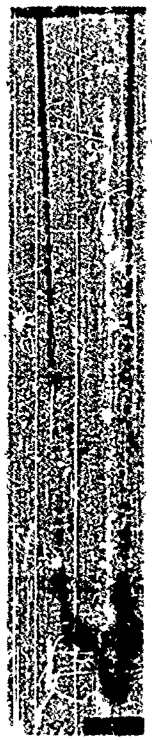

Figure 7

Multiple flash radiographs of the jet from a 105mm spun copper liner (Lot 2). The round was fired non-rotated.

Figure 8

Multiple flash radiographs of the jet from a 105mm spun copper liner (Lot 2). The spin rate was +15 rps. The jet is approaching spin compensation and the jet break-up is longitudinal.

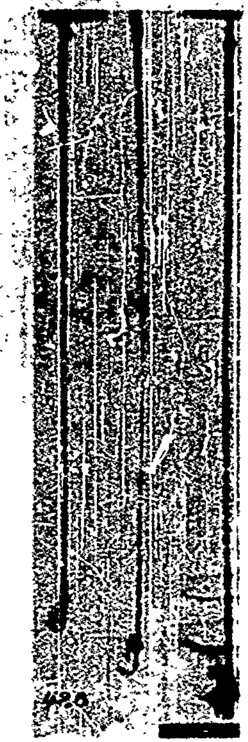

Figure 9

Multiple flash radiographs of the jet from a 105mm spun copper liner (Lot 2). The spin rate was +30 rps, the jet is approaching continuity.

Figure 10

Multiple flash radiographs of the jet from a 105mm spun copper liner (Lot 3). The spin rate was +45 rps. The jet is receding from the compensation frequency and the incidence of bifurcation may be seen.

Figure 11

Multiple flash radiographs of the jet from a 105mm spun copper liner (Lot 2). The spin rate was +60 rps. The jet is bifurcating and moving away from the compensation frequency.

various spin rates, are shown in Figures 1 to 5 for Lot 1, and in Figures 6 to 11 for Lot 2.

Examination of the radiographs shows that the jet of the liner behaves as expected in a liner with "built-in" spin compensation. At a zero spin-rate, Figure 2 (Lot 1) and Figure 7 (Lot 2), the jet is badly fragmented and bifurcated. At a spin frequency of +30 rps, the jet from both lots, Figure 4 (Lot 1) and Figure 9 (Lot 2), is continuous and slightly broken. Therefore, the spin compensation frequency lies in the neighborhood of +30 rps for both lots. A comparison of the jets in Figures 5 and 10, where both rounds were rotated at +45 rps, indicate that Lot 2 liners may have a higher spin compensation rate than Lot 1 liners. The jets from Lot 1 liners are further along in the bifurcation process at +45 rps.

Performance of Siliceous Cored Armor Against Shaped Charges* **

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Glass and other siliceous materials are commonly known to give superior performance on a weight basis against shaped charge weapons[1]. However, several attempts to develop practical armor utilizing glass has met with only limited success[2,3]. Recently, fused silica, having a melting point considerably higher than steel, was found to survive the casting of molten armor steel around it[4]. But although the fused silica core does not melt or change in physical appearance due to this treatment, some deterioration of its effectiveness against shaped charge jets does occur. This fact is verified by a comparison of its performance with that of an equivalent unconfined fused silica target. The core is thought to be damaged by severe inhomogeneous stresses applied to it during the casting and heat treatment.

Various designs of siliceous cored armor were tested against the M28A2 rocket charge fired at the built-in standoff and also against the Jet-Guns commercial shaped charge which is approximately a 0.7 scale model of the M28A2 charge. The latter charge was used to reduce expenditures of materials and to improve the statistical reliability of the results.

The most important consideration concerned with the application of siliceous cored armor is its weight relative to solid armor. For this reason, the performance will be discussed in terms of equivalent weight, that is, the ratio of the weight of cored armor to the weight of solid armor, both in the particular thickness required to completely stop the jet. The steel at the edges of the core is not considered part of the weight of the cored armor for the figures given below.

The following is a summary of the important results of tests on cored armor at Carnegie Institute of Technology:

(1) For penetration at normal incidence (perpendicular to the front surface), equivalent weights from 50 to 65 percent were obtained.

(2) For penetration at 60 deg. obliquity, equivalent weights ranging from 70 to 85 percent were obtained. Thus, there is a considerable loss of effectiveness experienced with highly oblique jet incidence, however, this loss is not as great as that for unconfined targets.

(3) Small area (less than 2 square feet) panels of a given thickness gave distinctly better results than large panels (12 square feet) of the same thickness and core configuration.

(4) Composite targets, made of glass cores confined solidly in steel boxes by pouring low melting metal (Woods Metal, melting point 156 deg. F.) into the interstices, performed considerably better

**Received 9 August 1955

than equivalent cored armor. This type of target yielded equivalent weights of less than 50 percent for normal jet incidence and approximately 60 percent for 60 deg. oblique attack. These figures should also be obtained for cored armor if the core damage is eliminated.

(5) Location of the core symmetrically in the armor gives improved performance. It is thought that the core is more nearly uniformly stressed because of its symmetric location, hence less damage is likely to occur.

(6) The total penetration for cored armor was less than that obtained with solid steel targets except for a few types shot at 60 deg. obliquity. Consequently, any practical cored armor that might be developed is not likely to be thicker than equivalent solid armor.

*The work described in this paper was carried out under Contract No. DA-20-089-ORD-36871 with Detroit Arsenal.

[1]"Protection Against Shaped Charges," Final Report OSRD No. 6384, 1946.

[2]E. M. Pugh, "Survey of Devices for Protecting Armored Vehicles Against Shaped Charges," Special Report No. 64, Contract No. W-36-[illegible]-ORD-2879, June 30, 1949.

[3]Flintkote Progress Report for the Period January 26, 1952 to February 26, 1952, Contract No. DA-30-069-ORD-245.

[4]E. C. Mutschler and R. V. Heine-Geldern, "Defeat of Shaped Charge Weapons," First Summary Report, Chapter IV, Carnegie Institute of Technology, January 1 to June 30, 1954, Contract No. DA-20-089-ORD-36871.

The Effect of Density in Confined Column Targets* **

E. C. Mutschler
Carnegie Institute of Technology, Pittsburgh, Pennsylvania

A number of tests have been conducted at Carnegie Institute of Technology with confined column targets ("water cells"), using a variety of materials of different density, in a standard setup consisting of a column 2 inches long and 1 inch in diameter. Confinement was a steel tube 1 inch thick, and a 1/2 inch steel cover plate was placed at the top of the column. These targets were tested against Jets-Guns charges at 3 inch standoff.

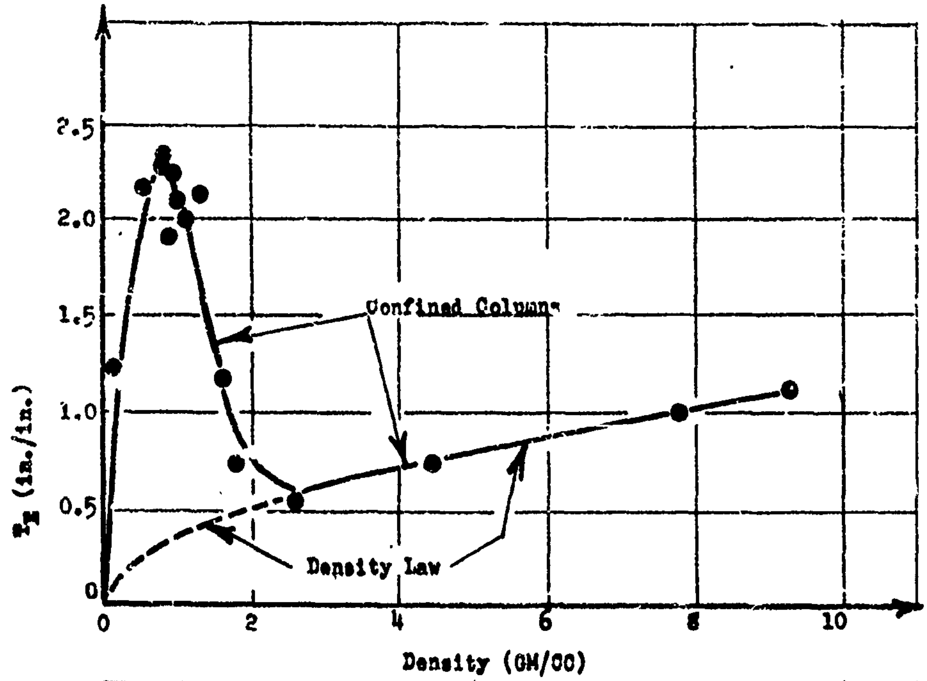
The results are shown in the plot of observed thickness equivalent (T_E) versus density of column material. T_E states the thickness of steel in inches that has the same jet-stopping power as 1 inch of column length, that is

$$T_E = \frac{\text{Penetration in steel} - \text{Penetration in steel for confined column targets}}{\text{length of column}} .$$

Also shown in this plot is the theoretical curve predicted by the simple density law of penetration. In the range of densities above 2.5 gms/cc, the two curves coincide and no effect due to confinement is apparent. However, below this range, the two curves diverge considerably indicating that an additional mechanism is effective for small densities. Flash X-radiographs and Kerr Cell pictures have furnished conclusive evidence that the residual jet is attacked by column material rebounding from the confining surround, thus accounting for the unusual effectiveness of the confined column targets.

The predominance of the confined column effect in the low density region is shown more vividly in a second plot in which the ratio of the observed thickness equivalent (T_E) to that predicted by the simple density law (T_E*) is given as a function of column density. Note that the axis of abscissae in this plot is considerably expanded as compared with the previous plot. Column materials having densities between 0.5 and 1.8 gms/cc lie on an almost straight line. Materials having densities greater than 1.8 gms/cc lie on a horizontal line at $\frac{T_E}{T_E*}$ equals 1, representing behavior according to the simple density law. This rather clearly defined limit for the "confined column effect" is quite interesting. It should be noted here that the results obtained are peculiar to the column geometry and the Jet-Gun charge and would vary somewhat for other conditions.

**Received 9 August 1955


Confined Columns
Density Law
Density (GM/CC)
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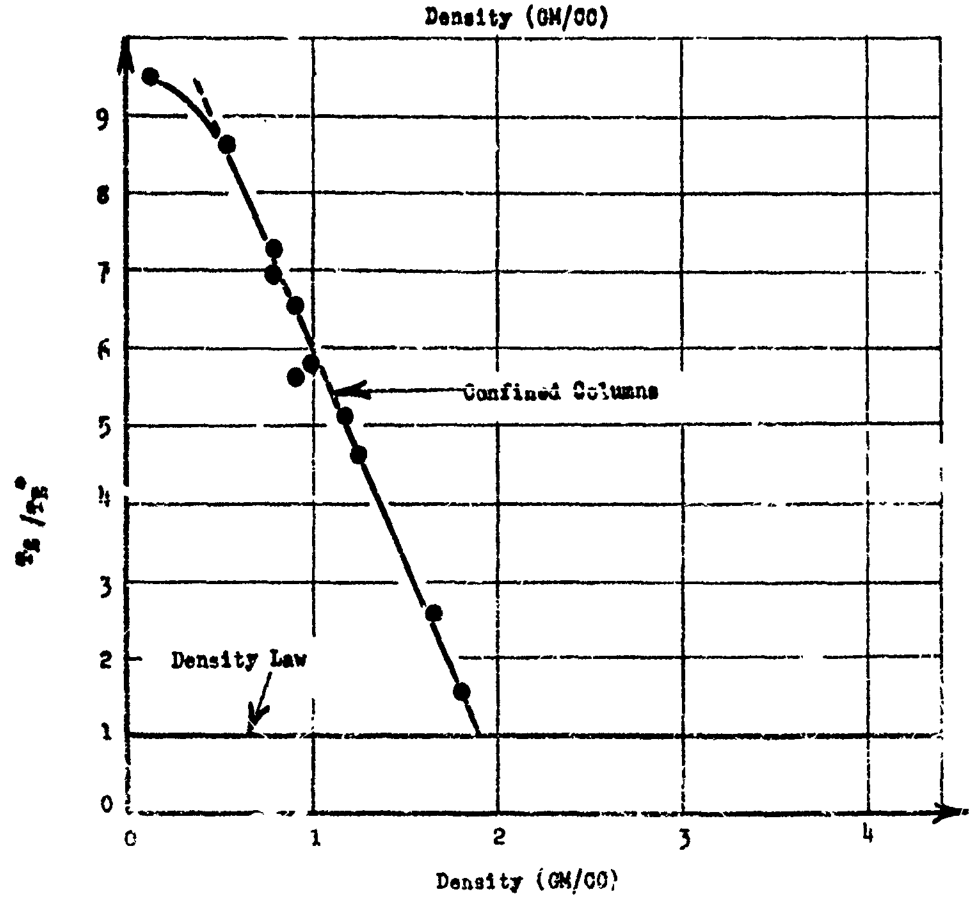
2.0
1.5
1.0
0.5
0
0
2
4
6
8
10


Confined Columns
Density Law
Density (GM/CC)
9
8
7
6
5
4
3
2
1
0
0
1
2
3
4

Density of the column material was used in these tests because other target characteristics that are likely to be important - namely, compressibility and shock velocity - are unknown for most of the materials under any conditions, and are unknown for all of the materials available for conditions prevailing during penetration by the shaped charge jet. The consistency of results obtained using density as an independent variable is remarkable, however.

*The work described in this paper was carried out under Contract No. DA-20-089-ORD-36871 with Detroit Arsenal.

Fracture of Steel Plates under Explosive Loading* **

T. P. Murray
Carnegie Institute of Technology, Pittsburgh, Pennsylvania

Recent experiments carried out at C.I.T. to gain basic information about the spalling process have yielded some interesting results. The experiments consisted of exploding cylindrical Comp. B charges of varying configuration in contact with armor plate and mild steel. The results show that for a certain range of charge parameters and plate thicknesses, the spalling process consists of the ejection from the plate of a large "plug" of the shape shown schematically in Fig. 1. Surfaces A and D are the original front and back surfaces of the target. Surface B has the smooth appearance characteristic of shear, while surface C has the rough, jagged appearance characteristic of tensile fracture.

It has been found that this plug ejection process is very sensitive to charge diameter, but relatively insensitive to charge length. For a charge diameter of 3 in., the plug is roughly hemispherical, with a small perforation in the top plate surface. For smaller diameters, a spall fragment is ejected from the back part of the plate and the plate is not perforated. With charge diameters exceeding 3.5 in., the plugs are of the shape shown in Fig. 1, and the diameters of surfaces A and D increase linearly with the charge diameter. (See Fig. 2). As an example, a charge 5 in. in diameter and 0.40 in. long results in a plug with diameter of 3.25 in. for surface A and a diameter of 5 in. for surface D.

For charges with a fixed diameter of 4 in. and lengths varying from 0.25 in. to 1 in., the resulting plugs all had diameters A of about 1.75 in. and diameters D of about 5 in., with a variation of about 0.25 in., so that the process is almost independent of charge length, providing the length exceeds a certain minimum. (See Fig. 3.) (A 1/8 in. charge produced only a crater in the target; no spall was ejected.)

All of the above described results were obtained with 1 in. armor plate. Similar results have been obtained with 0.5 in. and 1 in. mild steel targets.

From the initial experiments, it was believed that the sheared surface B could be attributed to the existence of a steep pressure gradient in the explosive products, which caused shearing to occur at the top surface of the target. It was thought that this shear then propagated back to intersect with the surface of tensile fracture initiated by the interaction of the compression wave and a tension wave originating at the back surface of the target. To check this hypothesis, charges were exploded in contact with 4 in. thick targets. It was believed that if this shear process occurred it would be evidenced by cracking in the thick targets. However, only small random cracking occurred; it appears that the sheared surface as well as the tensile fracture surface must originate in the interactions taking place at the target surfaces.

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**Received 9 August 1953

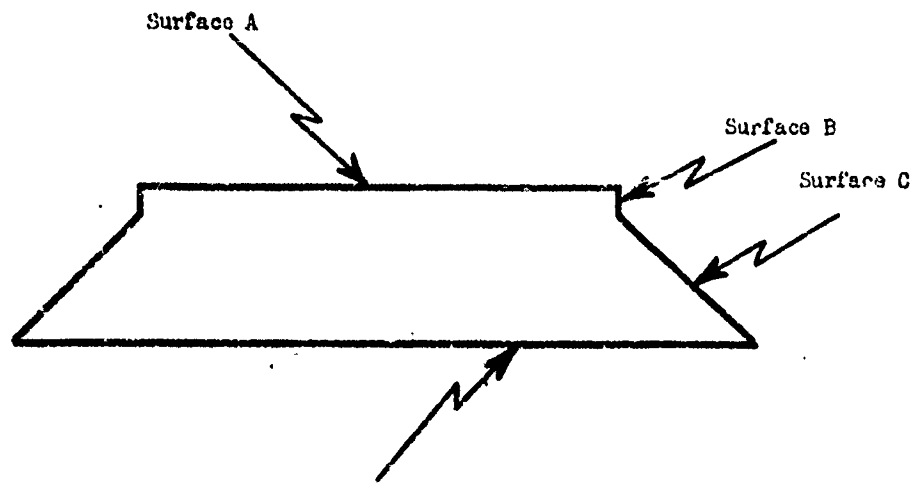

Figure 1: Sketch showing approximate shape of plug ejected by spalling.

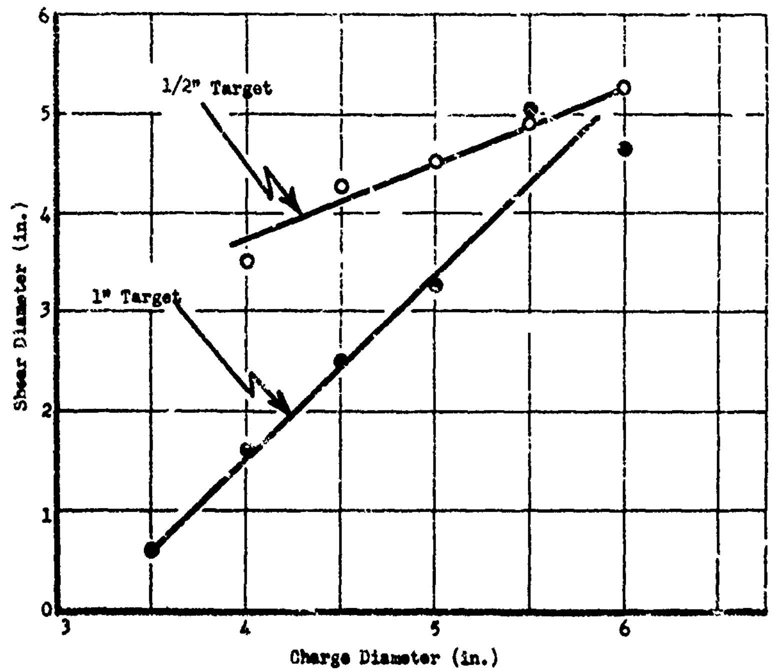

Figure 2: Shear Diameter as a function of charge diameter. (The ratio of charge diameter to charge length was held constant at 8).

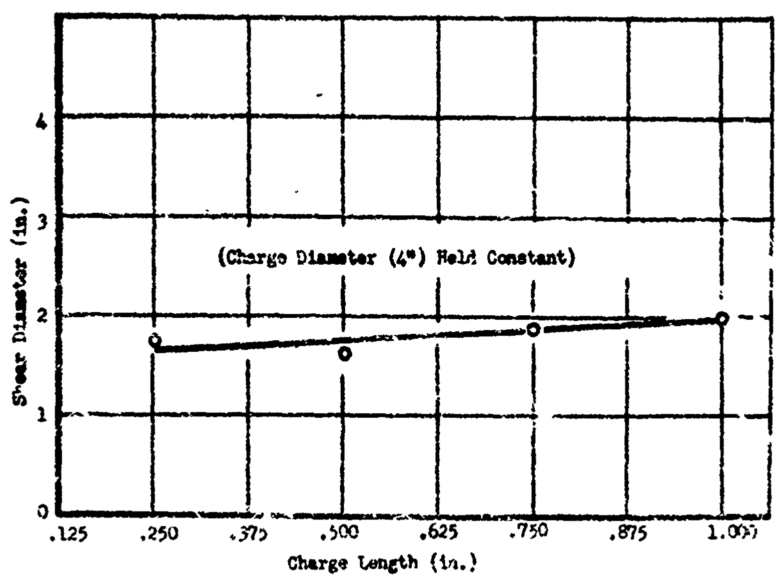

Figure 3: Shear diameter as a function of charge length with charge diameter constant at 4".

It may be that, as tensile fracture proceeds, sufficient momentum is trapped within the plug to enable it to free itself from the plate by shear when fracture has proceeded to within a certain distance from the top surface of the target plate.

It might be mentioned that 12 in. x 12 in. target plates were used for charges 4.5 in. and smaller in diameter, while 15 in. x 15 in. target plates were used for charges of diameter larger than 4.5 in., so that it is not believed that reflections from the sides of the target contribute anything to the spalling process observed.

In many cases the plugs recovered show another type of fracture in addition to that described above. In such cases the plugs are fractured completely across, parallel to the base, at a distance of about 0.25 in. from the back surface. This type of fracture has occurred with both 0.5 in. and 1 in. mild steel targets. It has not been observed in the few armor plugs obtained.

The simplest theoretical approximation to this problem is to consider the interaction between a spherical compression wave proceeding from a virtual source above the target and a reflected spherical tension wave proceeding from an image source below the target. This approach, which has been carried out by G. I. Taylor[1], predicts a fracture surface different from either of the two types discussed above.

It is believed that a more realistic and more detailed approach will be required to explain the actual fracture process observed. If an approximate theory can be developed, the symmetry of the experimental results is such that an adequate quantitative check on the theory is available.

*The work described in this paper was carried out under Contract No. DA-36-061-ORD-453 with Ballistic Research Laboratories and was reported in the Third Quarterly Status Report, July 31, 1955.

[1] W. M. Evans and Sir. G. I. Taylor, Research 5 (1952). p. 502.

A Theoretical Treatment of Crater Formation by High Velocity Fragments* **

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Carnegie Institute of Technology, Pittsburgh, Pennsylvania

A number of theories have been proposed for the formation of craters by high velocity projectiles; but, due to the scarcity of good data, these theories have been tested only for certain projectile types and limited velocity ranges. Thus it is not definitely known whether hole volume is a single valued function of fragment momentum or of fragment energy as predicted by certain theories based on various models of penetration.

On the basis of experiments with lead targets[1,2], the penetration by hypervelocity fragments may be described as the production of a hole by the hemispherical distribution of energy around the point of impact. Further, no permanent compression has been detected in cratered targets. Hence, we have developed another theory of crater formation which considers the struck target as an expanding hemispherical shell of incompressible fluid.

We assume that energy is conserved and that the crater forming process stops when the maximum pressure gradient within the target drops to a critical value. We find that

$$V^{4/3} \lambda^4 (\lambda - 1)(\lambda + 1)^{-5/3} (\lambda^2 + 1)^{-5/3} = (\pi/18750)^{1/3} \frac{E_f}{b} ,$$

where V is the hole volume, E_f is the fragment energy, b is the critical value of the pressure gradient, and $\lambda = 1 + V_T/V$, V_T being the hemispherical volume defined with the nearest distance from the center of impact to the back or side of the target as the radius. When $V \ll V_T$, V is proportional to $E^{3/4}$; but when $V \gg V_T$, V is proportional to E^3. For fixed E_f, we find that as V_T is decreased V increases slowly at first, then increases quite rapidly as V_T becomes small. This latter behavior should be easy to check experimentally, but no data are available as yet.

*Received 9 August 1955

**The work described in this paper was carried out under Contract No. DA-36-061-ORD-453 with Ballistic Research Laboratories and was reported in the Second Quarterly Status Report, April 30, 1955.

[1] R. J. Eichelberger, F. E. Allison, and W. F. Donaldson, "Craters Formed by High Velocity Fragments," Fundamentals of Shaped Charges, C.I.T. Status Report No. 3, Chapter I, Contract No. DA-36-061-ORD-394, July 31, 1954.

[2] R. J. Eichelberger and W. F. Donaldson, "Crater Formation by Hypervelocity Fragments," Fundamentals of Shaped Charges, C.I.T. First Quarterly Status Report, Contract No. DA-36-061-ORD-453, January 31, 1955.

FLASH RADIOGRAPHS OF STEEL BALLS PROJECTED THROUGH ARMOR BY A 3.5" SHAPED CHARGE CONTAINER ROUND*

J. Simon

Ballistic Research Laboratories
Aberdeen Proving Ground, Maryland

The Ballistic Research Laboratories[1] have designed a 3.5" lethality round which enables one to place a variety of materials in a container placed around the base of the liner as shown in Figure 1. The mechanism involves the projection by a shaped charge round of materials through a perforation made in a target by its jet.[2][3]

For this experiment, the follow-through material consisting of 3000 1/8" steel balls was placed in the container, and flash radiographs of the region preceding the slug were obtained. Figure 2 shows the pre-slug region after perforating 3" of armor at a 4.3" standoff by a 3.5" M28A2 rocket warhead. Figure 3 is a repetition of the same experiment with a container filled with steel balls. A comparison of Figures 2 and 3 shows that the ball bearings have been projected through the target plate.

The effectiveness of this type of round in the projection of lethal materials which are possibly toxic or incendiary has been illustrated by these radiographs.

(1) Breidenbach, H. I., and Gehring, J. Wm., Further Studies of Methods for Increasing the Destructiveness and Lethality of Lined Cavity Charges, BRL 951, APG, Md., August 1955.

(2) Breidenbach, H. I., A Study of a Method for Increasing the Lethality of Shaped Charges, Transactions of Symposium on Shaped Charges, held at the BRL, 7 - 11 December 1953, APG, Md., BRL 909.

(3) Simon, J., Flash Radiographs of Shaped Charges for Increased Lethality (U), BRLM 912, APG, Md. August 1955.

*Received 1 August 1955.

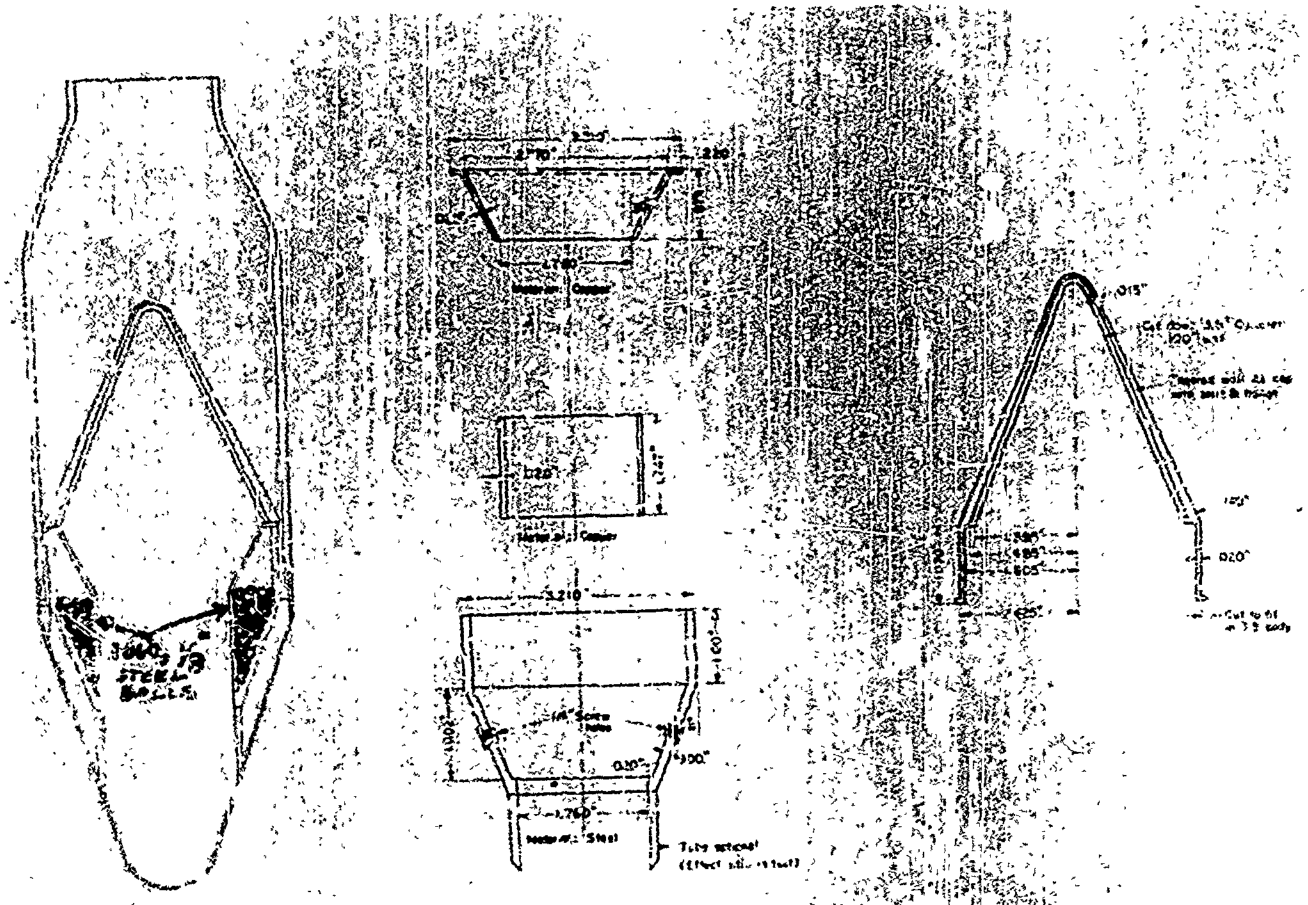

Figure 1

. . sembly and components of the modified 3. 5" M28A2, chemical container round, model 10. The location of the steel balls may be seen in the assembly.

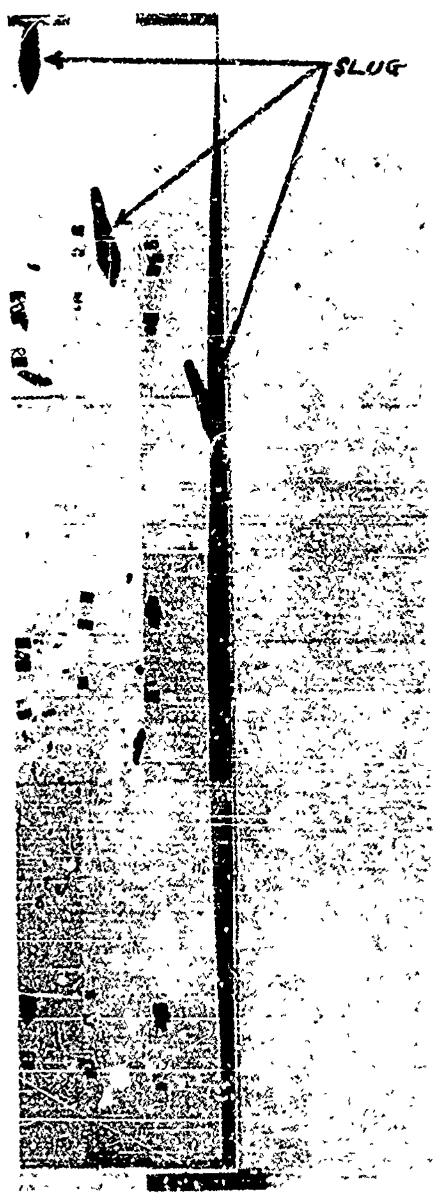

Figure 2

Flash radiographs of the slug from a 3.5" copper liner through a 3" homogeneous armor target at an ogive standoff of 4.3". The absence of any appreciable amount of fragments preceding the slug can be noted. Compare with Figure 3.

Figure 3

Flash radiographs of the "follow through" material projected through a 3" homogeneous armor target at a "built-in" ogive standoff at 4.3". The round fired through this target was a 3.5" M28A2 modified chemical container round. As a witnessing mechanism, 3000 - 1/8" steel balls were placed in the container.

FLASH RADIOGRAPHS OF BALLS PROJECTED THROUGH ARMOR FROM A 106MM SLEEVED SHAPED CHARGE LINER*

J. Simon

Ballistic Research Laboratories
Aberdeen Proving Ground, Maryland

The Ballistic Research Laboratories(1)(2)(3) have shown the feasibility of sleeved liners for shaped charge applications. A scaled-up version of the 1-5/8" round, the modified 106mm round, shown in Figure 1 was examined by means of flash radiography(4) to determine whether the collapse mechanism and jet formation was essencially the same as reported for the 1-5/8" round.

Radiographs, shown in Figures 2 and 3, of the pre-slug region of a standard 105mm T-138, and a 106mm lethality round with an ogive and aluminum capped liner containing 320 1/8" steel balls are compared in free flight. The lethality liner radiograph, Figure 3, shows the steel balls after they have funneled through the ogive followed by the collapsed aluminum cap carrier and slug.

The same rounds were fired at a built-in ogive standoff of 8" through 6" of homogeneous armor. The radiographs, Figures 4 and 5, give similar results to those of Figures 2 and 3. As may be observed in Figure 5, the radiograph of a sleeved liner, the addition of balls in the lower portion of the sleeve has resulted in successful projection through the hole made in the armor target. The divergence of the ball spray may be observed, and the extra material going through the hole contributes additional fragments near the axis of the hole.

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(1) Breidenbach, H. I., A Method for Increasing the Destructiveness and Lethality of Lined Cavity Charges, BRL 848, APG, Md. February 1953.

(2) Breidenbach, H. I., A Study of a Method for Increasing the Lethality of Shaped Charges, Transactions of Symposium on Shaped Charges, held at BRL, 7-11 December 1953, BRL 909, APG, Md.

(3) Breidenbach, H. I., and Gehring, J. Wm., Further Studies of Methods for Increasing the Destructiveness and Lethality of Lined Cavity Charges. BRL 951, APG, Md., August 1955.

(4) Simon, J., Flash Radiographs of Shaped Charges for Increased Lethality (U), BRLM 912, APG, Md., August 1955.

*Received 1 August 1955.

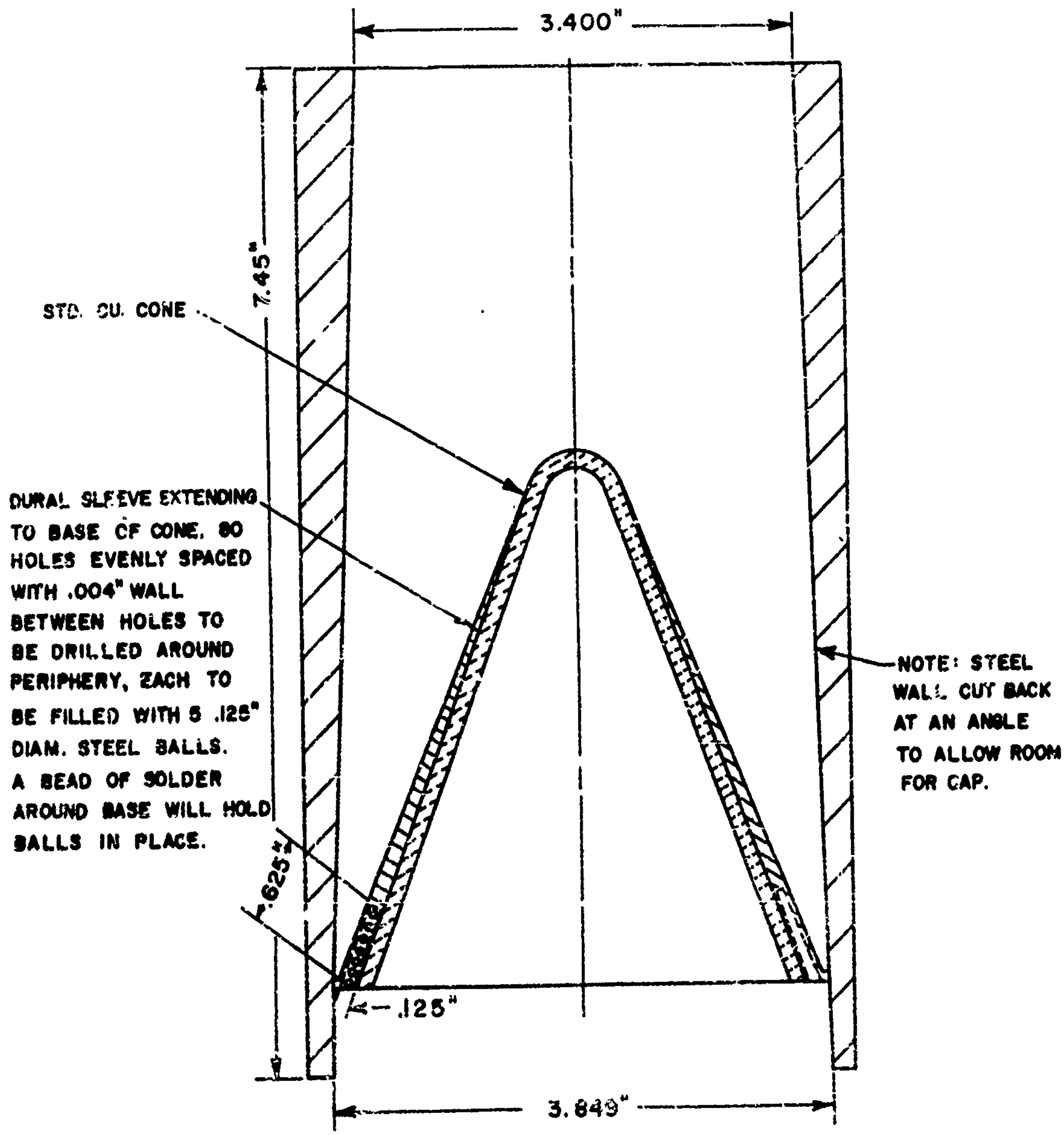


Figure 1

A sketch of the experimental 106mm sleeved, ball-projecting round.

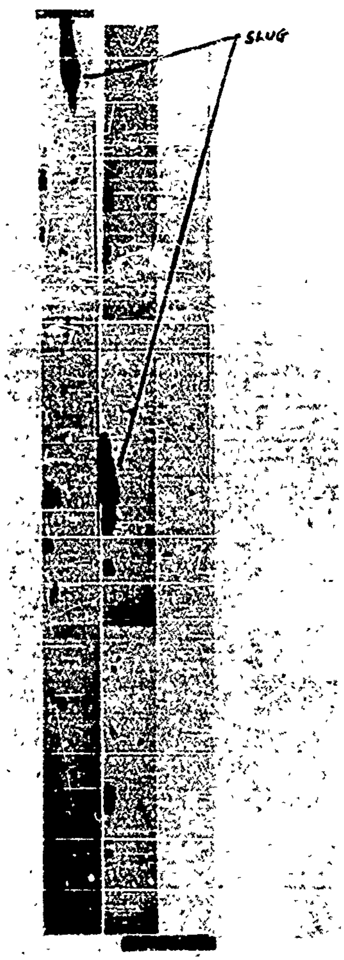


Figure 2

Flash radiographs showing the slug from a 105mm drawn copper liner and the secondary fragments preceding the slug. This round was fired without any target being placed in the path of the jet. A comparison with Figure 3 shows the absence of large numbers of fragments.

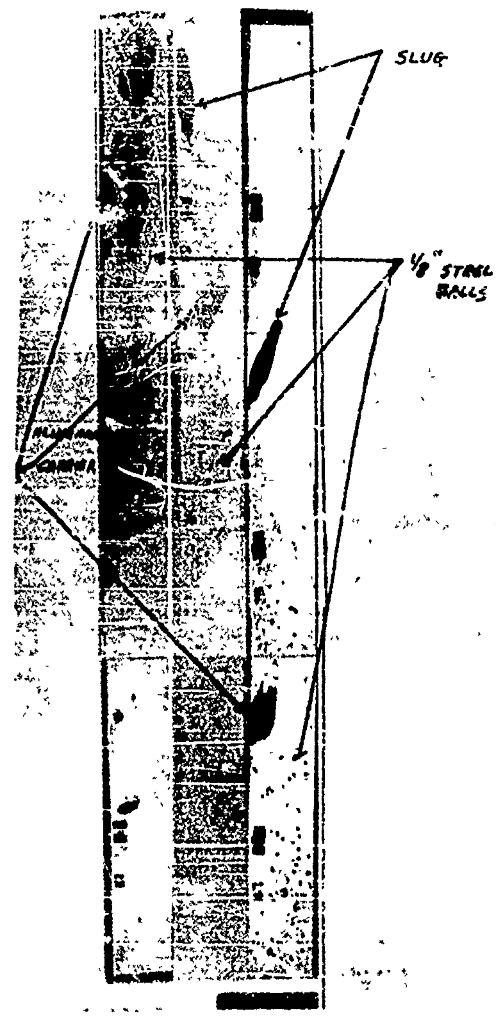


Figure 3

Flash radiographs of the jet, steel balls, aluminum sleeved carrier and slug of the 106mm sleeved liner design. These radiographs illustrate the "follow through" application without any target in the path of the jet. The secondary fragment spray consists of many of the original 320 - 1/8" steel balls.

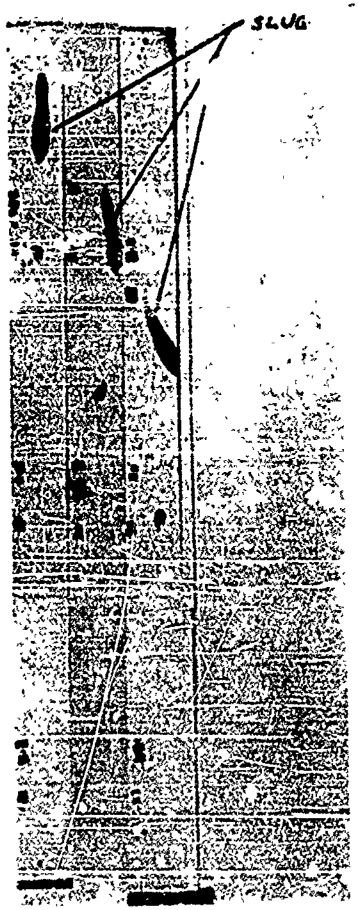


Figure 4

Flash radiographs of a 105mm standard drawn copper liner after it has been fired through 6" of homogeneous armor at an 8" ogive standoff. The region preceding the slug shows very few fragments. That figure should be compared with Figure 5.

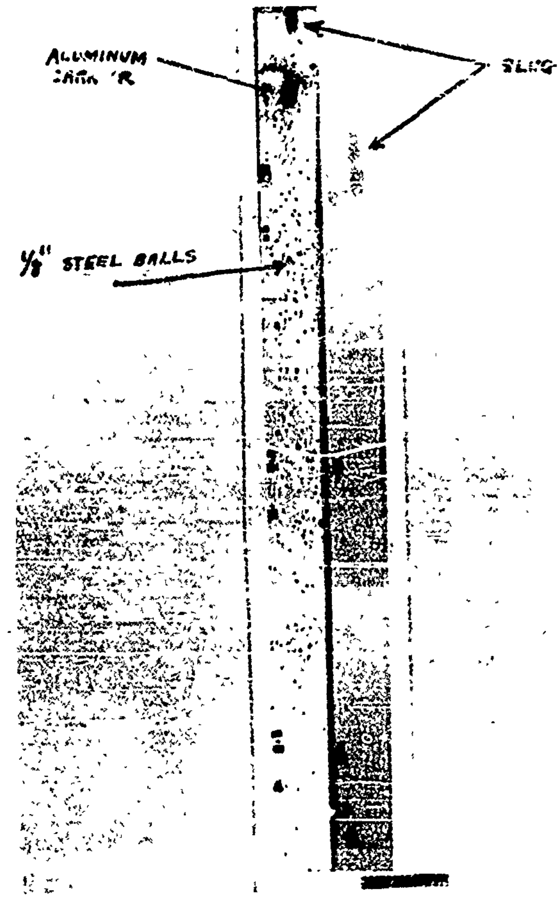


Figure 5

Flash radiograph of a 106mm sleeved liner ball design after it has penetrated 6" of homogeneous armor at an ogive standoff of 8". The "follow through" principle has not been destroyed by placing armor in the path of the jet. The secondary fragments, aluminum sleeved liner and slug appear in the same time sequency as seen in Figure 3.

Effect of the Fuse Conduit on the Long Standoff Performance of the M31 Rifle Grenade Charge* **

E. C. Mutschler
Carnegie Institute of Technology, Pittsburgh, Pennsylvania

In the course of shooting a penetration versus standoff curve for the M31 rifle grenade charge, a marked correlation was noted to exist, particularly at long standoffs, between the direction of the "keyhole" in the target and the orientation of the charge. At standoffs of 14 in. or longer the jet appears to produce a secondary penetration in the side of the hole (the hole resembles a keyhole) in the direction of the fuse conduit in the charge. This effect (keyholing) is known to result from a jet which has its back section displaced laterally from the front section, causing it to penetrate the target at a different point.

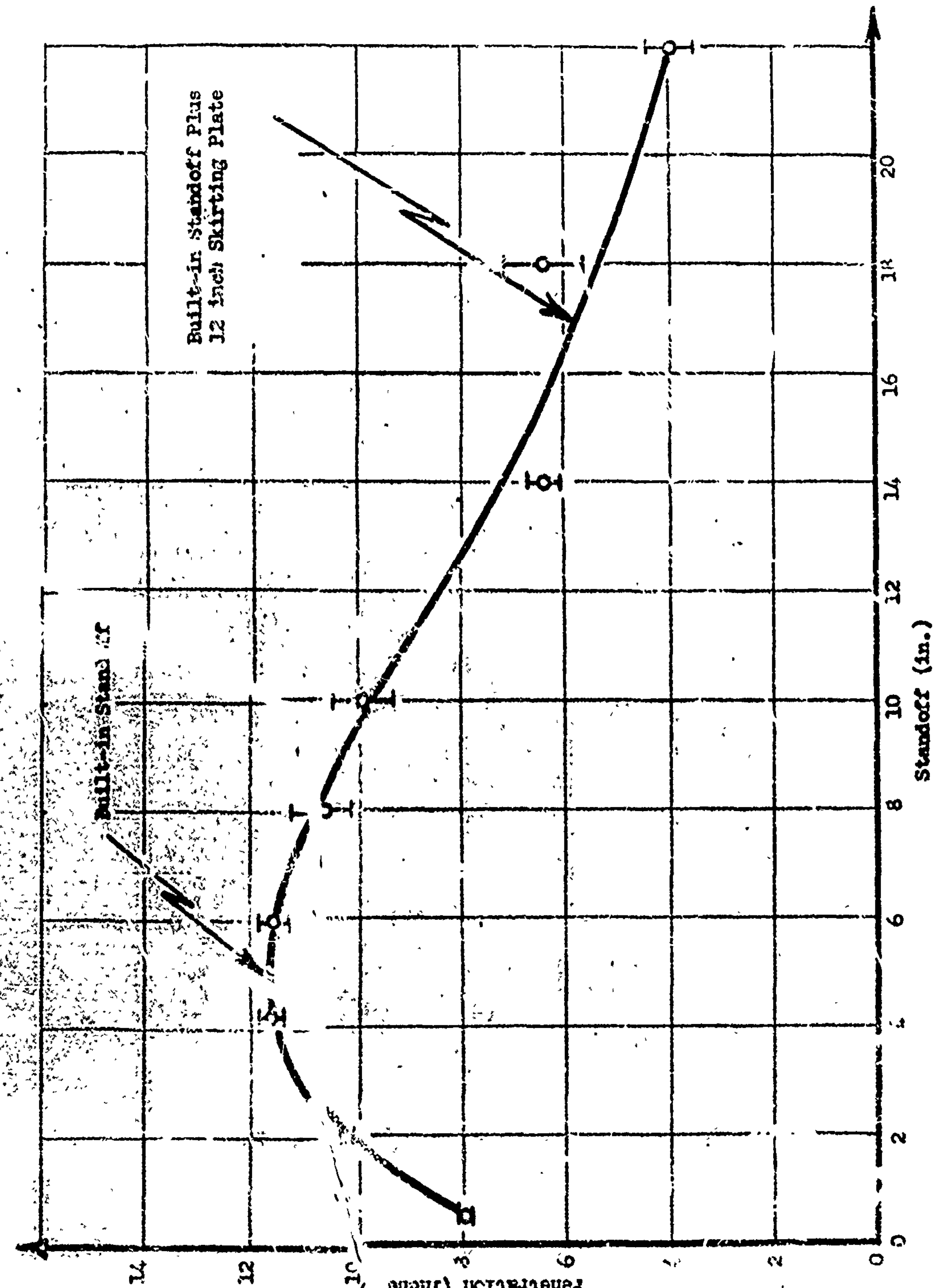
The fuse conduit is a 3/32 in. square brass tube that extends along the inside of the metal charge body from the nose fuse at the front of the ogive to the detonator at the far end of the charge. This tube passes through a slot cut into the liner base and is soldered in position at this point and at several other places along the charge body.

For charges shot at a 14 in. standoff, 8 out of 10 shots produced keyholes in the direction of the fuse conduit. For the 18 in. and 22 in. standoffs, 9 out of 10 and 8 out of 10 shots respectively produced the same effect. In addition, the direction of the slug, as indicated by the mark it makes on the target, likewise correlated with the orientation of the fuse conduit; the direction is opposite that of the keyhole, as would be expected. For the 30 shots at the standoffs mentioned above, 24 slug marks occurred in a direction away from the fuse conduit.

It appears certain from the correlations noted above that the fuse conduit contributes significantly to the relatively poor performance of the M31 charge at long standoffs. However, performance at such standoffs is not important unless skirting plates are used as a defense against this weapon. It can be seen from the penetration standoff curve that a 12 in. skirting plate would reduce the penetration by approximately 50 percent (from 11.6 in. to approximately 6 in.). The reduction in penetration due to the fuse conduit alone cannot be estimated, but the extent of the keyholes and the strong correlation note indicate that it is probably a considerable fraction of the total.

*The work described in this paper was carried out under Contract No. DA-36-061-ORD-453 with Ballistic Research Laboratories.

**Received 9 August 1955


Built-in Standoff Plus
12 Inch Skirting Plate
Built-in Standoff
Standoff (in.)
Penetration (inches)
0
2
4
6
8
10
12
14
16
18
20

FLASH RADIOGRAPHIC EXAMINATION OF JETS

FROM 106MM SHELL HEAT, T119E11 (M344)*

J. Simon
L. Zernow**

Ballistic Research Laboratories
Aberdeen Proving Ground, Maryland

Firings conducted in connection with the lethality program of the M344 HEAT shell gave average penetrations into homogeneous armor of 17.8" dynamically and 14.2" statically.(1) Since the shell rotated approximately +15 rps*** at target impact in the ballistic firings, a possibility of spin compensation existing in these liners was explored to determine whether it contributed to the ballistic penetration improvement over the static penetrations.

Representative samples selected from the remaining ammunition were made available for the flash radiography of jets from these liners. Three rounds with nose cap and fuze crystal intact were fired, and the jets radiographed at the zero spin rate (0 rps) and at ±15 rps.*** Figures 1, 2 and 3 show that the effect of rotation on the photographed jet is symmetric about the zero spin rate. These observations ruled out the possibility of spin compensation accounting for the improved ballistic performance over the static penetration.

It was thought that the nose cap and fuze crystal element might be in the way of the jet on the static tests, but removed from the path of jet in the ballistic tests. Figure 4 is the picture of a jet from a round fired at a zero spin rate with the front part of the ogive removed and shows that the jet is slightly broken up longitudinally. The degradation of the jet by the front part of the round and any secondary interference which might result from the crystal element is seen to be very slight, (c.f. Figures 1 and 4).

The slight degradation of the jet by the nose cap and fuze indicated by these radiographic observations is in qualitative agreement with the 1" difference in penetration observed (15.2" without fuze and 14.2" with fuze).(2) Thus the nose cap and fuze cannot account for all the difference between static and dynamic shots.

---

(1) Fifty-sixth Progress Report of the Firestone Tire and Rubber Company on Battalion Anti-Tank Project under Contract No. DA-33-019-ORD-1202, Firestone Tire and Rubber Company, Defense Research Division, Akron, Ohio, March 1955.

(2) Verbal communication by Dr. H. Winn, Firestone Tire and Rubber Company, Defense Research Division, Akron, Ohio.

* Received 2 August 1955.

** Dr. Zernow is now with Aerojet-General Corporation, Azusa, California.

*** The convention for algebraic sign of the direction of rotation has been taken as positive if rotation of the projectile is clockwise when viewed from the rear. This is the normal situation for artillery with a right hand twist of rifling.

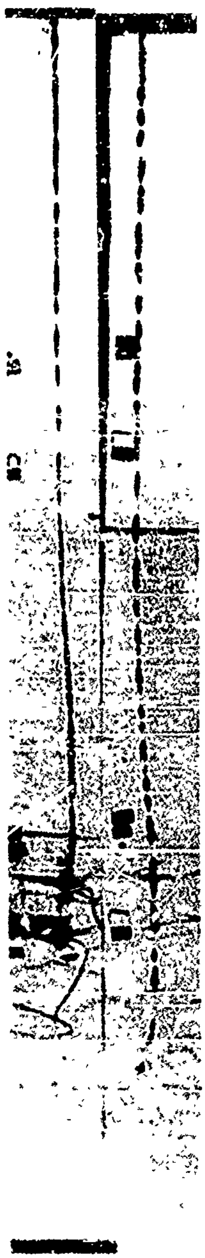


Figure 1

Flash radiographs of the jet from a 106mm, T119 liner. The round was fired statically. The nose cap and fuze crystal element were on the ogive in this firing.

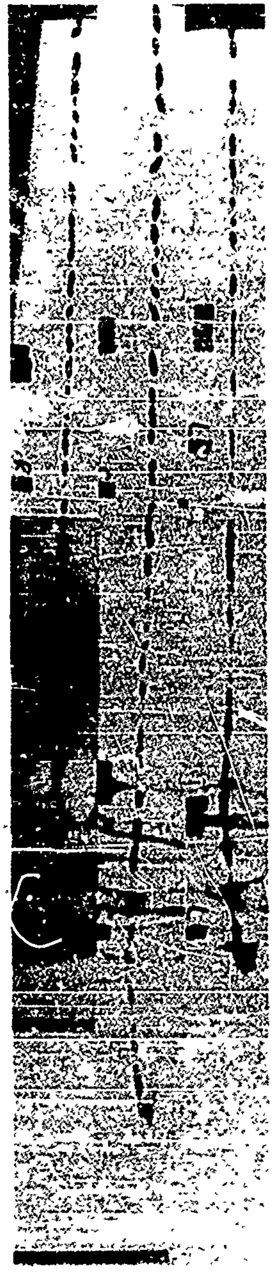


Figure 2

Flash radiographs of the jet from a 106mm, T119 liner. The round was rotated at +15 rps. The nose cap and fuze crystal element were in the path of the jet in this firing.

Figure 3

Flash radiographs of the jet from a 106mm, T119 liner. The round was rotated at -15 rps. The nose cap and fuze crystal element were in the path of the jet in this firing. This jet is similar to that of Figure 2, (rotated +15 rps), showing symmetry about the non-rotated frequency axis.

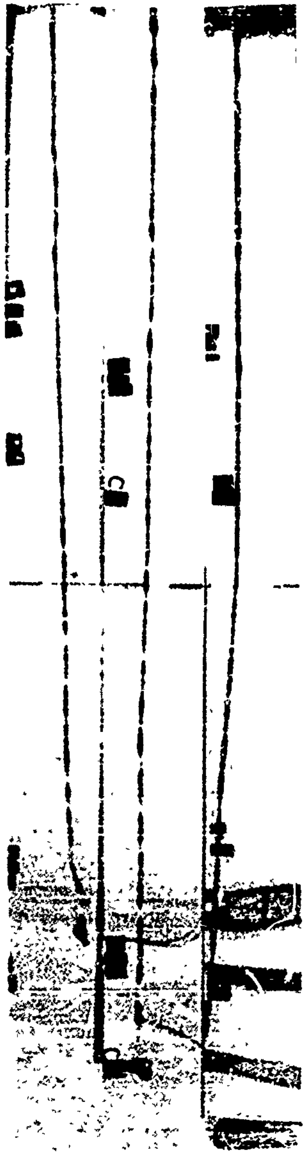


Figure 4

Flash radiographs of the jet from a 106mm, T119 liner. The round was fired statically with the nose cap and fuze crystal element removed. Compared with Figure 1, the jet of this figure more continuous, indicating jet removal passing through the nose cap, and fuze element.

Preliminary Evaluation of the Usefulness of Flash Radiographs for Quantitative Jet Studies* **

H. A. Holmes
Carnegie Institute of Technology, Pittsburgh, Pennsylvania

Exploratory experiments were carried out to ascertain the experimental difficulties involved in the use of low voltage flash X-ray[1] pictures for quantitative determinations of jet mass, elongation and fracture. The results were used solely to check the methods employed rather than to support or dispute data previously obtained by other methods.

The standard C.I.T. charge containing the M9A1 steel cone was used for the investigation because much information is available regarding the performance of this type of charge[2] which provided a check on the results obtained by the X-ray study.

The conditions which limited the accuracy of the measurements were: (1) Variations in the charge. (2) Variations in the timing circuit. (3) Multiple exposures. (4) Movements of the particles during the exposure time. (5) Differences in density due to variations in the intensity of the X-ray. (6) Observational error due to the judgment of the observer in determining the true boundaries of the particles. (7) Magnification factor.

The variation in the position of the tip of the jet, which is an indication of the extent of (1) and (2) above, was about 2 per cent. Many of the multiple exposures were eliminated from the study because successive portions of the jet particles overlapped making the actual boundaries of the particles too much in doubt. The error due (4) was negligible since the exposure time was very short. The variations of (5) produced some under-exposures for which there was a tendency to consider the particle larger than it actually was and some over-exposures for which the tendency was to consider the particle smaller than its true size. Although these under- and over-exposures should cancel to some extent, this is nevertheless considered to be the most serious source of error. An estimate of the error due to (6) was obtained by having several individuals measure the particle area on a given section of each picture. The error thus obtained for the pictures used in this study was 10 to 15 per cent. The magnification factor was computed and corrections made therefor.

The results gave some indication that the jet particles lengthen after the initial fracture; however, this is considered doubtful due to the uncertainty of the measurements. Although the data of this first exploratory experiment showed a great deal of variability, the results in general seem to agree with data previously obtained by other methods. There is an apparent need for refinements, but with improvements the methods used here give promise of yielding reliable information. Therefore, a similar study is being carried out using X-ray pictures which appear to be of more uniform density and a 3.23 in. diameter copper cone which will give larger fragments and thus reduce the percentage error in the measurements.

**Received 9 August 19[illegible]

*The work described in this paper was carried out under Contract No. DA-36-061-ORD-453 with Ballistic Research Laboratories and was reported in the Third Quarterly Status Report, July 31, 1955.

[1]J. J. Paszek, B. C. Taylor and J. L. Squier, "Low Voltage Flash Radiography," B.R.L. Memorandum Rpt. No. 645, February 1953, Aberdeen Proving Ground.

[2]R. J. Eichelberger, "Re-Examination of the Theories of Jet Formation and Target Penetration by Lined Cavity Charges," CEL Rpt. No. 1, Contract No. DA-36-061-ORD-394, Carnegie Institute of Technology, June 1954.

RADIOGRAPHY OF STEEL TARGETS TO MEASURE THE PENETRATION OF JETS*

J. M. Regan
J. J. P. zek

Ballistic Research Laboratories
Aberdeen Proving Ground, Maryland

Recent discussions at the Shaped Charge Committee Meetings have aroused interest in the methods used for the determination of depth of penetration in targets.

The target most commonly used at the present time at BRL is a stack of 6" x 6" x 3" blocks and the penetration is determined by counting the number of blocks completely penetrated and adding to this the penetration into the final, partially penetrated, block. The block, partially penetrated, is cut through the center of the hole thus exposing the depth.

When steel cylinders are used as targets the determination of the depth of penetration is more difficult. It is necessary to cut transversely somewhere near, but above, the bottom of the hole and then cut longitudinally to expose the depth.

In an effort to find some easier way to measure the depth of penetration into steel cylinders, radiography has been suggested. The Ballistic Research Laboratories conducted a simple experiment to determine the feasibility of radiography for this purpose. Steel blocks, from the same steel supply used for targets, were exposed to a one (1) curie Co^{60} source for 20 hours using Kodak type M film. Although the depth of penetration was readable to the nearest one-eighth inch, the radiographic quality was poor.

However, we believe improvements could be made in the quality by proper shielding from scattered radiation and the use of more sensitive films. Furthermore, the radioactive source would require the construction of a special housing facility. In any case there is no increase in precision of measurement and no decrease in the time necessary to obtain the final measurement.

Since radiography offers no advantages over the method presently used here at these laboratories, its use is not contemplated. However, at installations where heavy duty power tools are not available for cutting blocks, a system of this sort may be particularly useful.

*Received 15 August 1955

CONFIDENTIAL

Improvements in Light Leakage and Light Source Intensity for Kerr Cell Photography* **

E. C. Mutschler, T. P. Murray and M. A. Holmes
Carnegie Institute of Technology, Pittsburgh, Pennsylvania

In Kerr cell photography it is desirable to eliminate light leakage as completely as possible. Therefore a system consisting of a polarizing filter, a Kerr cell, a second polarizing filter with its axis crossed at 90 deg. to the first, another Kerr cell, and a third filter with its axis parallel to the first was examined as a possible replacement for the usual single cell with two crossed filters[1].

From photographs it was estimated that two polarizing filters with their axes parallel and one with its axis at 90 deg. to the other two permitted light leakage about 100 times less than two filters with their axes crossed at 90 degrees. However, readings obtained by using a photocell and galvanometer show that three filters with their axes parallel transmit only 67 per cent as much light as two filters.

To take advantage of this better closing of the Kerr cell, it would be necessary to sacrifice about one-third of the light available when only two filters are used plus the amount of light lost due to the nitrobenzene in the additional cell.

Consequently, an attempt was made to develop a light source of greater intensity and, if possible, shorter duration than the exploding wire being used with two polaroids. Wires of different material and size, metal ribbons, paper moistened in water or acid and coated with powdered metals, and a glass plate over which a spark could glide were tested in the exploding wire circuit. This circuit includes a 3 microfarad condenser which is charged to 23 kilovolts and discharged through a wire causing the wire to explode and thus create a light source of very high intensity[2]. A 10 centimeter length of 0.005 in. aluminum wire is generally used and the materials tested were compared to this as a standard.

The best results were achieved using the 0.005 in. aluminum wire sandwiched between two 1/8 in. thick glass plates and viewed through the plates. Oscillograms show that the peak light obtained from this arrangement is 2.5 to 3 times that of the aluminum wire alone and that the duration of the peak is only about 0.6 that of the aluminum wire alone. These results were verified in a similar circuit with a 3 microfarad condenser at 20 kilovolts. Due to the glass plates, the luminous envelop surrounding the wire presents a greater area and more light in the direction of the photocell pickup. The shorter duration may be attributed to a quenching action by the shattering glass.

**Received 24 May 1955

*The work described in this paper was carried out under Contract No. DA-36-061-ORD-453 with Ballistic Research Laboratories.

[1]H. Schardin and E. Funfer, "Report on the Fundamentals of Spark-Cinematography," Zeitschrift fur Angewandte Physik, 4 Band, Heft 6, June 1952.

[2]S. Foner, R.v. Heine-Geldern and E. C. Mutschler, "High Speed Photography," Fundamentals of Shaped Charges, Eighteenth Bimonthly Report (CIT-ORD-21), Part II, p. 80, Contract No. W-36-061-ORD-2879, June 30, 1949.

Strain-Free Cells for Kerr Cell Photography* **

M. A. Holmes, T. P. Murray and E. J. Mutschler
Carnegie Insitute of Technology, Pittsburgh, Pennsylvania

Considerable difficulty has been encountered in obtaining the strain free absorption cells necessary for Kerr cell photography. Very high requirements must be placed on the optical properties of the cell to achieve a minimum of light transmission when the cell is placed between crossed polaroids[1]. If these requirements are not met, light leakage during the exploding of the wire light source (approximately 50 microseconds) will cloud a photograph taken with a Kerr cell opening of less than one microsecond.

From an order for seven strain free cells, none were usable due to the above failure. For this reason it was decided to construct a cell using as a cement a sodium silicate and talcum mixture[2]. No heat is required for such a seal and thus the possibility of inducing strains in the cell is reduced.

Glass 1/2 in. thick was used for the bottom and sides of the cell to provide considerable areas of contact, while the front and rear pieces were of 1/8 in. thickness because thinner glass is less likely to contain strains. A mixture of sodium silicate and talcum, approximately the consistency of molasses, was used as a binder. Extensive experiments to determine the optimum ratio of sodium silicate to talcum were not carried out, but apparently a wide range of mixtures would be satisfactory.

This binder was also found to be effective for joining glass to brass and one cell was made using brass for the main part of the body with thin glass windows cemented to the ends.

When tested between crossed polaroids no indication of strain could be detected in cells made with the sodium silicate and talcum cement. In addition to the test for strains, the cell was also filled with nitrobenzene and allowed to stand more than a month to determine whether the nitrobenzene would creep through the cemented area. At the end of this period of time no leakage could be detected although the seal can be completely dissolved in water.

*Received 24 May 1955

**The work described in this paper was carried out under Contract No. DA-36-061-ORD-453 with Ballistic Research Laboratories.

[1]R.v. Heine-Geldern, "High Speed Photography," Fundamentals of Shaped Charges, Fourth Bimonthly Report (CIT-ORD-39), p. 9, Contract No. DA-36-061-ORD-122, June 30, 1952.

[2]H. Schardin and E. Funfer, "Report on the Fundamentals of Spark-Cinematography," Zeitschrift fur Angewandte Physik, 4 Band, Heft 6, June 1952.

USE OF SHAPED CHARGES IN PHOTOFLASH BOMBS*

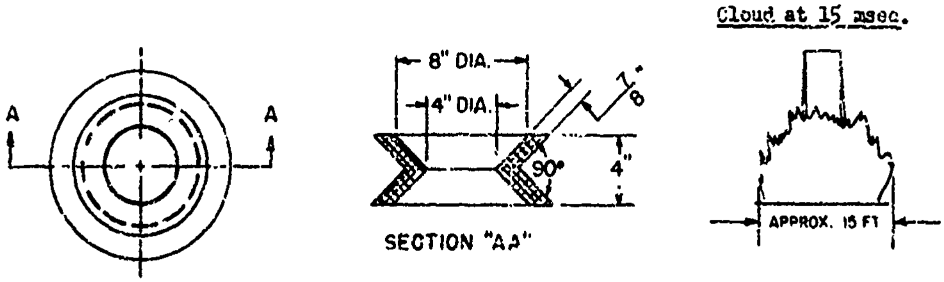
G. R. Handrick and E. L. Kreidl
Arthur D. Little, Inc.

In connection with the study on photoflash bombs, it appears that the light emission of only a rather thin layer of the cloud of burning or luminescent metal powder will contribute to the illumination of the ground. It, therefore, was believed desirable to devise means for spreading a photoflash or metal powder into a relatively thin sheet to obtain better use of the light emitted from the burning particles and incandescent combustion products. Some preliminary experiments have shown that a crude version of a shaped charge design can be quite effective in achieving this. Double channels of aluminum sheet were fabricated with 90° and with 45° angles and filled with magnesium, aluminum, or inert simulants, such as aluminum oxide. The channels were in the form of a straight line charge of circular or polygonal shape. High speed photographs (3000 frames/sec and 64 frames/sec) gave an indication that even in a crude design the metal can be thrown into a significantly flatter and longer pattern than possible in conventional design. The drawings illustrate the general shape of the items, and comparative sizes of burning clouds produced at approximate peak illumination. The clouds shown here were viewed side on with a slow motion color camera. Additional work is planned.

This work was done in co-operation and under contract with the Pyrotechnics Section of Picatinny Arsenal, and has received Project Officer approval for publication in the Shaped Charge Journal.

*Received 2 June 1955

SHAPED CHARGES FOR PHOTOFLASH BOMBS



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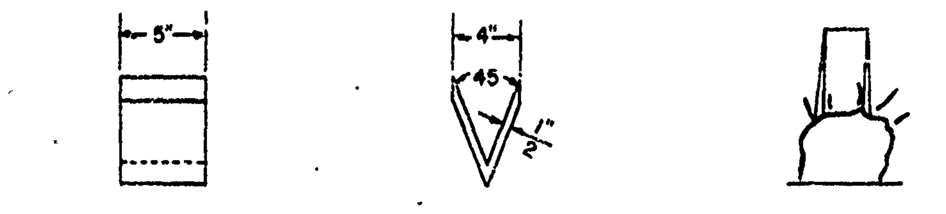

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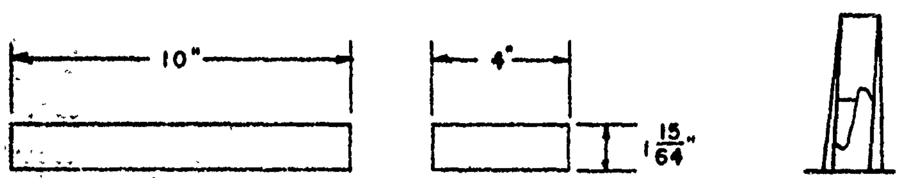

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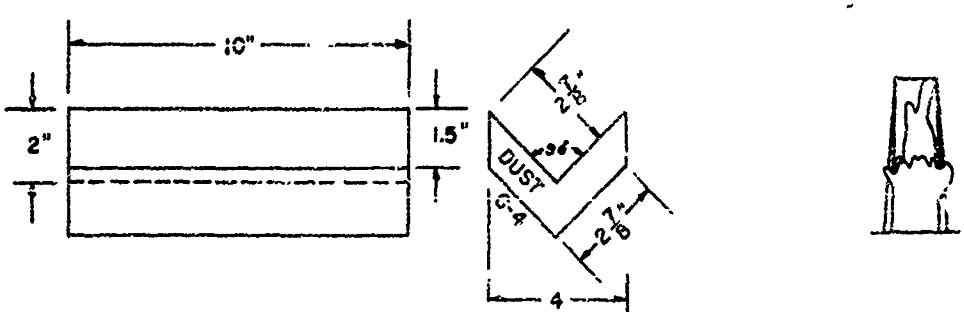

Item 7. Scale: 1/4" = 1"

CALENDAR OF COMING EVENTS

Listed here are events of general interest to those working in this and related fields. Further information about the meetings listed below can be obtained by writing to the addresses indicated in parentheses. Information concerning other such events for listing will be appreciated.

OCTOBER

11 - 12 Eighth regular meeting of the Ordnance Corps Shaped Charge Research and Development Steering and Coordinating Committee, Detroit Arsenal, Center Line, Michigan (Office, Chief of Ordnance, Department of the Army, Washington 25, D. C., Mr. Melvin C. Miller, ORDTB).

A B S T R A C T

I N D E X   C A R D S

First Section

This first section consists of index file cards, each bearing a brief abstract of a technical report, paper, or progress summary appearing in this issue of the Research Report.

It is intended that these cards can be removed for filing if desired. However, for security purposes, since the abstract may be classified, provision is made for retaining the signature and identification of the person removing the index card.

THE EFFECT OF SHAPED CHARGES AT LONG STANDOFF AGAINST AIRCRAFT, by R. G. S. Sewell, L. N. Cosner, J. Pearson, U. S. Naval Ordnance Test Station, China Lake, California

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The Effect of Shaped Charges at Long Standoff Against Aircraft

S. C. Report No. 4-55 October 1955

R. G. S. Sewell, L. N. Cosner, J. Pearson, U. S. Naval Ordnance Test Station, China Lake, California

The Naval Ordnance Test Station is continuing the investigation of the effects of shaped charges at long standoff against aircraft structures. The damage mechanisms are described, and an attempt is made to explain the processes active in producing vaporific explosions. The results of recent firings against aircraft structures prove conclusively that shaped charges can produce immediate or K-type kills against bomber style aircraft by means of vaporific explosions.

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5 pp. 0 figs.

PICATINNY ARSENAL SHAPED CHARGE COMMITTEE: ABSTRACTS OF PROCEEDINGS, FIRST HALF OF 1955.
C. G. Dunkle, Picatinny Arsenal, Dover, New Jersey CONFIDENTIAL

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Picatinny Arsenal Shaped Charge Committee: Abstract of Proceedings, First Half of 1955

S. C. Report No. 4-55 October 1955

C. G. Dunkle, Picatinny Arsenal, Dover, N. J.

Information reported in the three meetings showed progress in: (1) dissemination of new data (ADL shaped charge literature review) (2) improvement of metal parts (rotation compensation and investigation of fabrication processes) (3) improvement of the explosive charge (press-loading investigation, R-salt composition, tandem shaped charges), (4) defense, lethality and beyond-armor damage (density law deviation, billets vs plates, fragment distribution).

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Ordnance Corps Shaped Charge Research Report — S. C. Report No. 4-55, October 1955

Editors: John L. Squier, BRL, APG, Md.
Irving Lieberman, BRL, APG, Md.

Includes: Minutes of Seventh Meeting of Ordnance Corps Shaped Charge Committee; four papers presented at the meeting: Comments on Targets Used at the Ballistic Research Laboratories; Use of Steel Billets as Targets in the Evaluation of the Performance of Shaped Charges; Current Work on the Nitroso-analog (R-salt) of RDX for Application to Shaped Charges; The Effect of Shaped Charges at Long Standoff Against Aircraft; One Summary: Picatinny Arsenal Shaped Charge Committee - Abstracts of Proceedings, First Half of 1955; and 22 Letters to the Editor: Predicted Effects of Confinement on Shaped Charge Performance; The Distribution of Metals in a Jet from a Bi-Metal Liner; Note on

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Editors: John L. Squier, BRL, APG, Md.
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Second Section

The remainder of the abstract cards, which follow, are for reports and papers other than those published in the Research Report. These abstracts were submitted by the agencies originating the reports.

It is intended that these cards can be removed for filing if desired. However, for security purposes, since the abstract may be classified, provision is made for retaining the signature and identification of the person removing the index card.

SOME OBSERVATIONS OF ELASTIC PROPERTIES OF SOLIDS UNDER EXPLOSIVE LOADING, BRL No. 931,
by J. Dewey, H. I. Breidenbach, Jr., J. W. Gehring, Jr., BRL, APG, Md.

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BRL No. 931
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Some Observations of Elastic Properties of Solids under Explosive Loading

J. Dewey, H. I. Breidenbach, Jr., J. W. Gehring, Jr.,
Ballistic Research Laboratories, Aberdeen Proving Ground, Maryland

The strains and shock fronts in a magnesium alloy subjected to a contact detonation have been determined from flash radiographs. From these the stresses and stress-strain ratios for the compressional and shearing strains at the shock fronts have been computed, using finite strain theory. The compressional stress-strain ratio exceeds the infinitesimal and increases rapidly with strain. The shearing stress-strain ratio is considerably lower than the infinitesimal and about that predicted from Murnaghan's second order theory, μ-p. Much less complete

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AN EXPERIMENTAL DETERMINATION OF DETONATION PRESSURE IN TWO SOLID HIGH EXPLOSIVES, BRL No. 935
by J. W. Gehring, Jr., J. Dewey, BRL, APG, Md.

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An Experimental Determination of Detonation Pressure in Two Solid High Explosives

BRL No. 935
April 1955

J. W. Gehring, Jr., J. Dewey, Ballistic Research Laboratories, Aberdeen Proving Ground, Maryland

A method of determining detonation pressure of solid explosives by flash radiography of steady state contact detonations is described. Results on 50-50 Pentolite and Composition B are somewhat higher than computed values usually reported.

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